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Development and Application of an Approach to Optimize Renewable Energy Systems in Afghanistan

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THESIS

DEVELOPMENT AND APPLICATION OF AN APPROACH TO OPTIMIZE RENEWABLE ENERGY SYSTEMS IN AFGHANISTAN

by

Derek J. Law and Scott M. Tyley

June 2012

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Energy systems in Afghanistan are currently limited to diesel only solutions. The U.S. Army Corps of Engineers (USACE) do not have means to optimize various energy solutions when designing or modifying Afghanistan National Security Force (ANSF) installations in Afghanistan. The logistics of transporting diesel fuel increases risk to personnel and operations security, and can have a myriad of obscured costs. The purpose of this research is to develop an approach to prioritize multiple stakeholder needs and optimize a power portfolio based on actual environmental conditions. The approach seeks to reduce problems associated with fossil fuel systems by supplementing diesel generators with renewable energy solutions. The approach produces the data necessary to generate a rubric containing optimal combinations of energy systems to include both renewable and diesel power sources. The rubric aids in determining energy system characteristics for any given location in Afghanistan. The results demonstrate millions of dollars in savings while simultaneously reducing risk to operations and personnel in Afghanistan. This approach can be adapted to any region on the globe.

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ABSTRACT

Energy systems in Afghanistan are currently limited to diesel only solutions. The U.S. Army Corps of Engineers (USACE) do not have means to optimize various energy solutions when designing or modifying Afghanistan National Security Force (ANSF) installations in Afghanistan. The logistics of transporting diesel fuel increases risk to personnel and operations security, and can have a myriad of obscured costs. The purpose of this research is to develop an approach to prioritize multiple stakeholder needs and optimize a power portfolio based on actual environmental conditions. The approach seeks to reduce problems associated with fossil fuel systems by supplementing diesel generators with renewable energy solutions. The approach produces the data necessary to generate a rubric containing optimal combinations of energy systems to include both renewable and diesel power sources. The rubric aids in determining energy system characteristics for any given location in Afghanistan. The results demonstrate millions of dollars in savings while simultaneously reducing risk to operations and personnel in Afghanistan. This approach can be adapted to any region on the globe.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAF	Anti-Afghanistan Forces
AGM	Absorbed Glass Mat
AHP	Analytic Hierarchy Process
ANA	Afghanistan National Army
ANDS	Afghanistan National Development Strategy
ANP	Afghanistan National Police
ANSF	Afghanistan National Security Forces
AT&L	Acquisition, Technology, and Logistics
CBO	Congressional Budget Office
CJCS	Chairman of the Joint Chiefs of Staff
CIA	Central Intelligence Agency
COIN	Counter Intelligence
CRS	Congressional Research Service
DESC	Defense Energy Support Center
DOD	Department of Defense
DSB	Defense Science Board
DUSD	Deputy Under Secretary of Defense
ExFOB	Experimental Forward Operating Base
FBCF	Fully Burdened Cost of Fuel
FOB	Forward Operating Base
FY	Fiscal Year
GHG	Greenhouse Gas Emissions
HOMER	Hybrid Optimization Model for Electric Renewables

HOQ	House of Quality
HVAC	Heating, Ventilation, and Air Conditioning
IED	Improvised Explosive Device
ISAF	International Security Assistance Forces
KW	Kilowatt
MADM	Multi-Attribute Decision-Making
MRES	Multi-Attribute Decision-Making for Renewable Energy Systems
NDIA	National Defense Industrial Association
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
NSS	National Security Strategy
O&M	Operations and Maintenance
O&S	Operations and Sustainment
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
ONE	Operation Noble Eagle
ODASA-CE	Office of the Deputy Assistant Secretary of the Army for Cost and Economics (ODASA-CE)
OSD/CAPE	Office of the Secretary of Defense, Capability Assessment Program Evaluation
PV	Photovoltaic
QFD	Quality Function Deployment
RDECOM	U.S. Army's Research, Development, and Engineering Command
SARI	South Asia Regional Initiative
SAW	Simple Additive Weighting

SIGAR	Special Inspector General for Afghanistan Recovery
TPM	Talking Point Media
UNAMA	United Nations Assistance Mission in Afghanistan
USACE	U.S. Army Corps of Engineers
USAF	United States Air Force
USD/AT&L	Under Secretary of Defense for Acquisition, Technology and Logistics
USECAF	Under Secretary of the Air Force

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EXECUTIVE SUMMARY

Energy plays a vital role in several areas affecting the success of Afghanistan in achieving its objective of being a secure and sovereign nation capable of sustaining its own defense and economy (Afghanistan National Development Strategy, 2008). Reliance on fossil fuel energy systems poses a variety of problems such as logistical burdens, security risks, environmental concerns and increased life cycle costs. The current logistics and supply chain systems in Afghanistan are riddled with corruption (Tierney, 2010). The current energy construct puts significant risk on personnel responsible for transporting fuel.

Afghan National Security Forces (ANSF) currently rely heavily on diesel fueled generators to power the vast majority of the police and defense energy needs. Current U.S. Army Corps of Engineers (USACE) practices for implementing energy systems for ANSF infrastructure are limited to diesel generators, and, thus, preclude alternative energy solutions. This poses a security risk as evidence of IED attacks on fuel and support convoys. Senior military leaders' testimonies reinforce these risks and plead for alternative energy solutions (Mullen, 2010).

An approach is required to aid in implementing an optimal portfolio of renewable and non-renewable energy systems. The purpose of this thesis is to develop such an approach utilizing a multi-attribute decision-making (MADM) (Yoon and Hwang, 1995) based process to demonstrate its application for ANSF installations in Afghanistan. The approach constructs a MADM process for renewable energy solutions (MRES) to determine better energy systems by identifying optimal energy portfolios utilizing a combination of renewable and non-renewable energy solutions for Afghanistan.

Recent progress has been made with respect to renewable energy portfolio decision processes. For example, interactive and dynamic energy

modeling tools to understand life cycle implications for a variety of energy portfolio decisions have been developed (Ender et al., 2010). Ender's work provides the basis for an approach that includes a MADM process for renewable energy solutions in Afghanistan.

The approach to energy system decision-making, developed in this research, is broken into three phases: the generation of inputs, the MRES process, and the generation of an optimal energy rubric. The first phase of the approach is to develop the required inputs for the MRES process. There are three primary inputs: stakeholder needs, an energy load profile, and renewable energy parameters.

Stakeholders and their needs are each prioritized using the analytic hierarchy process (AHP) (Saaty, 1982). There are four stakeholder needs: increase security, minimize environmental impact, minimize initial cost and minimize life cycle cost. These needs are then reprioritized based on stakeholder weight using Brassard's full analytical criteria method for prioritization (Brassard, 1989). Brassard's method is based on Saaty's AHP methodology (Saaty, 1982). This method involves factoring in the weights of the individual stakeholders and the unique weights of their individual needs to reprioritize and assign a single weight value to each need.

The scope of the energy portfolio is defined through the generation of an hourly energy load profile and specific renewable energy parameters. A 24-hour load profile represents an Afghan National Police station or an Afghan National Army base. Since hourly data is unavailable, the load profile from the Marine Corps' Experimental Forward Operating Base (ExFOB) is used. This profile sufficiently represents smaller ANSF installations. Renewable energy parameters consist of hourly solar irradiance data, hourly wind potential, and the specific hardware used in producing and storing this energy.

In the second phase of the approach, the MRES, utilizes the quality function deployment (QFD) method (Akao, 1994) to map stakeholder unique

needs to key system attributes. This process translates four stakeholder needs into eight key system attribute values: total O&M cost, renewable fraction, generator production, wind production, solar production, battery quantity, life cycle cost and initial capital cost. QFD results in eight weighted values for each of the eight key system attributes.

The MRES process also requires the energy load profile and renewable energy parameter inputs. The inputs feed directly into the Hybrid Optimization Model for Electric Renewables (HOMER), computer simulation software developed by the National Renewable Energy Laboratory. This software provides the simulation necessary to develop the trade space for all the potential combinations of systems that meet the given load profile. The simulations are repeated 28 times to address every combination of solar irradiance and wind potential throughout Afghanistan. For each regional combination, HOMER analyzes approximately 9,000 different system combinations for a total of 252,000 distinct systems combinations.

The MRES process concludes with optimization. Optimization involves scaling all of the outputs from the simulation. Then the simple additive weighting (SAW) technique obtains a score (as the product of the weighted system attributes developed from QFD and the scaled energy system metrics from the simulation), and selects the highest score corresponding to the optimal energy portfolio for a given location.

The third and final phase of the approach is to develop an optimal energy rubric. The output of the MRES process produces the data necessary to generate a rubric with optimal combinations of energy systems to include solar, wind, and diesel energy sources. The rubric contains unique system configurations for all environmental conditions throughout a given region. The rubric permits engineers the ability to quickly identify the optimal energy system portfolio based on stakeholder needs.

The optimal energy rubric is significant because there is not just one optimal energy system design for all of Afghanistan. The optimal design depends heavily upon the measure of solar irradiance and wind speed for a given location. The optimal energy rubric generated herein identifies 19 specific energy system designs that are optimized for any location within Afghanistan's borders.

The benefits of this approach when applied to Afghanistan include reductions in fuel consumption and subsequently, reductions in security risk, energy dependence, environmental impact, energy and life cycle cost. The 25-year life cycle cost of an optimized energy system portfolio consisting of renewable and diesel energy systems is $1,911,481, while the diesel generator only system is $5,093,536. The USACE have plans to construct an additional 600 ANSF facilities in Afghanistan (USACE, 2011). Applying this approach to these construction projects would save $1.8 billion dollars over the next 25 years. Fewer diesel fuel transport convoys reduce the opportunity for bribery and corruption that are currently hindering security efforts in Afghanistan today. Security risks are further reduced by minimizing the number of logistics runs and exposure to IEDs. This approach is not exclusive to Afghanistan; it can be adapted to any region on the globe.

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I. INTRODUCTION

Reconstruction efforts in Afghanistan lack decision-making tools to aid in the development of the energy infrastructure (Brummet, 2010). The absence of an energy systems modeling tool limits information needed for sustainable and economical energy optimization. Ecological and socio-economic factors need to be included in the up-front decision-making process (Ender et al., 2010). Over-reliance on energy systems utilizing solely fossil fuels poses various problems such as: (a) logistics burdens (Thomas & Kerner, 2010), (b) increased security risks resulting from fuel logistics and fuel availability (Eady et al., 2009; Mullen, 2010; Tierney, 2010), (c) environmental concerns (Defense Science Board, 2008), and (d) increased costs (Lovins, 2010; Ender et al., 2010). These problems, discussed in Section A, motivate an examination of renewable and sustainable energy systems.

A multi-attribute decision-making (MADM) process is needed to aid in optimizing renewable/non-renewable energy combinations. To satisfy this need, an approach is presented that optimizes energy system portfolios based on stakeholder needs, an energy load profile, and environmental inputs. This approach is detailed in Chapter II, its utility and application are illustrated in Chapter III, and the results are discussed in Chapter IV.

A. BACKGROUND

1. Problem Domains with Fossil Fuel Energy Systems

a. Logistics Burden

In a 2010 audit of Afghanistan's current energy supply, the special inspector general for Afghanistan reconstruction (SIGAR) stated that "Afghans rely primarily on electricity produced by costly diesel generators as opposed to lower cost options such as imported power or natural gas, hydro, solar, and wind energy which are or could be generated within Afghanistan" (Brummet, 2010, p. 2). Consequently, the primary energy solution for the Afghanistan National

Security Forces (ANSF), which is comprised of the Afghanistan National Army (ANA) and the Afghanistan National Police (ANP), is fossil fuel (Brummet, 2010). The Afghanistan National Development Strategy (Nadiri, 2008) states that, “isolated diesel generation has dramatically increased since 2002 and will continue to play a large role in power supplies” (Nadiri, 2008, p. 78). Fossil fuel comes with a considerable and complex system that is dedicated to the transportation and storage of fuel. Ashton Carter, while serving as the U.S. undersecretary of defense for acquisition, technology and logistics (USD/AT&L), stated in an interview with the *Washington Post* that, "getting into Afghanistan…is very difficult because next to Antarctica, Afghanistan is probably the most incommodious place, from a logistics point of view, to be trying to fight a war" (Mufson and Pincus, 2009, para. 3). Afghanistan poses several challenges to easy access, including unsecure neighboring countries controlled by governments with strained relations to the United States and challenging local terrain such as the Hindu Kush mountain range (Tierney, 2010). Afghanistan’s lack of suitable airports and fuel distribution pipelines limits the military’s ability to rely on air transport. Consequently, 80% of goods reach Afghanistan by land. This offers a challenging environment to gain entry into the country and to transport supplies throughout the country.

Daily use of huge quantities of fuel increases transportation and logistics costs. When the Army deploys, half of the tonnage is fuel (Eady, 2009). More than a half-million gallons of fuel are required for a single marine combat brigade in one day (Lovins, 2010). Supplying such large quantities of fuel into Afghanistan is a tremendous burden on logistics brigades. Moreover, it places increased demand on the security personnel and infrastructure to ensure the supply lines are safe and operational (Lovins, 2010).

The Department of Defense commissioned a study by the defense science board in 2001 on the fuel efficiency of weapons platforms. The study indicated that the U.S. Army committed 40,000 soldiers to performing jobs related to fuel logistics (DSB, 2001). This reduces the number of soldiers that

are available for positions directly related to the mission in Afghanistan. If the demand for diesel fuel is reduced, logistic requirements lessen, thereby increasing personnel for direct mission operatives.

Figure 1. A C-130 Hercules airdrops supplies to a forward operating base in Uruzgan Province, Afghanistan. (From: Rose, 2011)

Figure 1 captures an airdrop consisting of fuel and water to resupply a forward operating base (FOB) in Afghanistan. The total cost of these supplies has historically not accounted for the logistical support required to deliver the supplies to the final location. This logistical support includes the aircraft, fuel consumed to drop the supplies, pilots, aircrew, the airbase, air traffic control, the personnel who received the goods on the ground and the equipment used to transport it to the FOB for storage. Michael Mullen (2010), Chairman of the Joint Chiefs of Staff (CJCS), stated at an energy security forum regarding renewable energy:

> When we consider the estimates of a fully burdened cost of diesel fuel approached $400 a gallon…these benefits [energy conservation techniques] start to really add up. This translates to fewer Marines maintaining fuel storage and distribution systems, fewer Marines dedicating their lives to protect the convoys in the routes used to deliver the fuel…(Mullen, 2010)

b. Security Risks

Transporting fuel into Afghanistan reflects a high operation tempo requiring extensive personnel (e.g., soldiers, marines, and airmen) to execute the logistics. Lovins (2010) reports that, “logistics uses roughly half the department’s personnel” (Lovins, 2010, pg. 34). Predictable transportation routes for fuel increase risk for extortion and attack (Tierney, 2010). Consequently, the DoD provides measures to decrease the loss of life for convoy personnel by providing aerial surveillance and security support from helicopters and close air support platforms. In 2009, Ashton Carter, indicated that “despite extensive land and air forces trying to guard them…fuel convoys are attractive and vulnerable targets, making them one of the Marine Corps commandant’s most pressing casualty risks in Afghanistan” (Lovins, 2010, p. 34).

Figure 2 depicts a fuel convoy in Afghanistan along mountainous terrain. This is a typical route for some forward operating bases that need regular resupply of diesel fuel to power installations in Afghanistan.

Figure 2. A fuel convoy in Afghanistan. (From: Deloitte, 2009)

Another security risk associated with fuel logistics pertains to the reliance on foreign governments to supply fuel. Mullen (2010) suggested a need to “rethink our view on energy and minimize our dependence on overseas energy sources that fuel regimes that do not always share our interests and values” (Mullen, 2010, para. 6). If fuel imports to Afghanistan ceased unexpectedly, this would increase vulnerability for operations in theater and security to U.S. personnel (Defense Science Board, 2001).

The commanding general of the first Marine Expeditionary Brigade at Camp Pendleton, Richard Zilmer (2006), declared the need for an alternative solution:

> …that reduces the number of convoys while providing an additional capability to outlying bases—to augment our use of fossil fuels with renewable energy, such as photovoltaic solar panels and wind turbines, at our outlying bases. (Bishnoi, 2006, para. 5)

Zilmer further stated:

> By reducing the need for [petroleum-based fuels] at our outlying bases, we can decrease the frequency of logistics convoys on the road, thereby reducing the danger to our marines, soldiers, and sailors. (Bishnoi, 2006, para. 5)

Transporting fuel into and throughout Afghanistan is life threatening (Under Secretary of Defense (AT&L), 2009). “For example the casualty factor for fuel resupply in Afghanistan is 0.042; that is 0.042 casualties for every fuel-related resupply convoy or one casualty for every 24 fuel resupply convoys in Afghanistan” (Eady et al., 2009, p. i).

Another security concern relates to the fuel distribution scheme in Afghanistan and the susceptibility to fraud, waste, and abuse. The fuel supply management system in Afghanistan is riddled with corruption, and, consequently, the U.S. Congress directed an investigation in 2010. This investigation was led by the committee on oversight and government reform, chaired by U.S. Representative John Tierney, and executed by the subcommittee on national security and foreign affairs. One of the main findings by the investigation is:

> The Department of Defense designed a contract that put responsibility for the security of vital U.S. supplies on contractors and their unaccountable security providers. This arrangement has fueled a vast protection racket run by a shadowy network of warlords, strongmen, commanders, corrupt Afghan officials, and perhaps others. Not only does the system run afoul of the Department’s own rules and regulations mandated by Congress, it also appears to risk undermining the U.S. strategy for achieving its goals in Afghanistan. (Tierney, 2010, p. 3)

U.S. Congressman Darrel Issa, in the context of the same investigation, commented in an interview with *Talking Point Media* that "It's not like you have a credit card and can track these things like you do at the local pump" (Crabtree, 2011, para. 5). The congressman further elaborated that “the estimated stolen fuel in both Afghanistan and Iraq could well amount to a billion-dollar loss for the DoD” (Crabtree, 2011, para. 5). Tierney’s 2010 investigation, *Warlord Inc.*, reported that the host nation trucking (HNT) contract is worth

approximately $2.16 billion and amounts to 6,000 to 8,000 supply truck missions per month (Tierney 2010, p. 1). The report also found “the largest private security provider for HNT trucks complained that it had to pay $1,000 to $10,000 in monthly bribes to nearly every Afghan governor, police chief, and local military unit whose territory the company passed (Tierney, 2010, p. 3).

World-wide dependence on fossil fuel for energy limits U.S. partnerships when dealing with rogue nations with oil supplies as Lengyel (2007) explains:

> Many nations dependent on consuming imported oil makes them reluctant to join coalitions led by the United States to combat weapons proliferation, terrorism, or aggression. Examples include French, Russian, and Chinese resistance to sanctions on Iran; Chinese resistance to sanctions against Sudan; and US tolerance of Middle East repression that would otherwise have been sanctioned, were it to occur in any other non-oil-producing part of the world. (Lengyel, 2007, pp. 34–35)

c. Environmental Impact

Fossil fuel-based energy has a negative impact on the environment and human health. According to the U.S. Environmental Protection Agency (EPA), 22.2 pounds of carbon dioxide (CO_2) is produced when a gallon of diesel fuel is burned (EPA, 2005). Carbon dioxide is a greenhouse gas that is linked to global climate change (EPA, 2011). The U.S. Energy Information Administration (EIA) also found in 2009 that “petroleum is the largest fossil fuel source for energy-related CO_2 emissions, contributing 43% of the total” (EIA, 2009, p. 2). The EIA 2009 study further reported “in December 2009, the EPA issued its final endangerment and cause or contribute findings for greenhouse gas emissions from light-duty vehicles, classifying them as a danger to public health and welfare” (EIA, 2009, p. 11).

The EIA also reports that increasing greenhouse gas emissions warm the planet’s surface (EIA, 2009). The intergovernmental panel on climate change (IPCC) concluded at its 2007 working group that:

> There is general agreement that health co-benefits from reduced air pollution as a result of actions to reduce GHG emissions can be substantial and may offset a substantial fraction of mitigation costs (Barker et al., 2001, 2007; Cifuentes et al., 2001; West et al., 2004). A portfolio of actions, including energy efficiency, renewable energy, and transport measures, is needed in order to achieve these reductions (IPCC, 2011, para. 1).

Reducing carbon monoxide emissions is a major initiative among the world's leading powers with committees including Kyoto and Montreal protocols and the United Nations framework on climate change (UNFCCC) actively pursuing and enforcing climate regulation. In 2009 the U.S. enacted policy to reduce carbon emissions by 28% by 2020 (Office of the Press Secretary, 2010, para. 1).

According to the Defense Science Board in 2008:

> An important and growing issue affecting energy is global warming. In the U.S., oil, coal and natural gas supply about 85% of total energy, and all produce greenhouse gas emissions (GHGs). Since the U.S. is responsible for more than 20% of annual worldwide emissions, global warming has become a major geopolitical issue, with international pressure growing for the U.S. to take a more active leadership role to address it. Many of our closest allies consider global warming among their most important issues. (DSB, 2008, p. 21).

The international scientific and academic communities have acknowledged the adverse impact of fossil fuels on the environment.

d. Cost

"DoD is probably the world's largest institutional oil buyer, consuming in the 2008 fiscal year 120 million barrels consisting of $16 billion, or 93% of all U.S. government oil use" (Lovins, 2010, p. 34).

Fuel is a significant contributing factor to the total cost of war. The total cost of the war in Afghanistan is projected to rise or remain at current levels with FY 2010 funding levels (Belasco, 2011). The CRS report states:

> The cost of the Afghan war has risen dramatically since FY2006, as troop levels and the intensity of conflict has grown, increasing from $19 billion in FY2006 to $60 billion in FY2009. Assuming administration requests are approved, total war funding will rise to $105 billion in FY2010 and $119 billion in FY2011. (Belasco, 2011, p. 19)

President Barack Obama, who recognizes this risk and highlighted it repeatedly in his National Security Strategy (NSS), stressed that the "development of new sources of energy will reduce our dependence on foreign oil" (Obama, 2010, p. 2), and that the U.S.:

> Must transform the way that we use energy—diversifying supplies, investing in innovation, and deploying clean energy technologies. By doing so, we will enhance energy security, create jobs, and fight climate change. (Obama, 2010, p. 10)

The President's NSS summarized that:

> As long as we are dependent on fossil fuels, we need to ensure the security and free flow of global energy resources. But without significant and timely adjustments, our energy dependence will continue to undermine our security and prosperity. This will leave the U.S. vulnerable to energy supply disruptions, manipulation and to changes in the environment on an unprecedented scale. (Obama, 2010, p. 30)

Costs associated with the war in Afghanistan are escalating and this promulgates greater risk to achieving the war objectives and operations security (DSB, 2008). The Congressional Budget Office (CBO) estimates that "over the next ten years, the war costs for DoD, State, and Veterans Affairs could require an additional $496 billion, assuming troop levels fall to 45,000 in 2015 and remain at that level" (Belasco, 2011, p. 20). The CBO estimate is a staggering amount equaling roughly one-third of the total war expenditures since 2001. These costs must drive initiatives to pursue cheaper and more efficient alternatives for providing power to facilities in Afghanistan.

The defense energy support center (DESC), the agency responsible for purchasing all U.S. fuel in support of military operations, purchased diesel fuel for use in Afghanistan at $4.18/gallon in FY 2011 (DESC

2011). The DESC price of fuel does not account for the fully burdened cost of fuel for the region (DSB, 2008). The DUSD/AT&L mandated in 2007, that all future systems perform an analysis to understand the fully burdened cost of fuel. The U.S. deputy undersecretary of defense for acquisition technology and logistics (DUSD/AT&L) memo specifically states:

> Effective immediately, it is DoD policy to include the fully burdened cost of delivered energy in trade-off analyses conducted for all tactical systems with end items that create a demand for energy and to improve the energy efficiency of those systems, consistent with mission requirements and cost effectiveness. (U.S. Deputy Under Secretary of Defense AT&L, 2007, para. 3)

The office of the Deputy Assistant Secretary of The Army for cost and economics (ODASA-CE) created the 7-step fully burdened cost of fuel calculation tool depicted in Table 1 (Hull, 2010).

Step	Burden Element
1	DESC Commodity Cost of Fuel
2	Primary Fuel Delivery Asset O&S Cost
3	Depreciation Cost of Primary Fuel Delivery Assets
4	Direct Fuel Infrastructure O&S and Recapitalization Cost
5	Indirect Fuel Infrastructure O&S Cost
6	Environmental Cost
7	Other Costs (i.e. Force Protection)

Table 1. FBCF 7-Step Process. (From: Hull, 2010)

DESC controls the first step and simply uses the negotiated cost of fuel, in this case, diesel fuel in Afghanistan as the commodity cost of fuel. The next step incorporates the operations and sustainment costs of the primary fuel delivery asset. For Afghanistan, the operations and sustainment costs are fuel trucks that transport the fuel to Afghanistan from fuel suppliers in foreign countries such as Pakistan (Tierney, 2010). The cost of operating and sustaining these trucks is largely a direct cost from U.S. defense contractors to perform maintenance functions. The third step in the process accounts for the depreciation of the delivery assets, in this case fuel trucks. For example, trucks

have a limited life from operating in the harsh and extreme environments of Afghanistan and from operating on poor road systems common in a third world country. This depreciation cost, under direction of the DUSD/ATL, should be incorporated into the cost of fuel (U.S. Under Secretary of Defense AT&L, 2009). The next step is intended to account for the cost of operating and sustaining the infrastructure necessary to store the fuel in Afghanistan. The fuel brought into Afghanistan is not delivered directly to every base or facility in theater, but rather to large logistical hubs staged in various locations around the country (Tierney, 2010).

The direct costs from O&S would include defense contractors who work, operate, and repair the fuel logistics equipment (U.S. Under Secretary of Defense AT&L, 2009). In addition, the FBCF model also considers indirect costs from these facilities. This would include electricity, waste disposal, water, and other costs not directly attributed to fuel costs (U.S. Under Secretary of Defense AT&L, 2009). Moreover, users must consider the environmental costs. Permits are required to operate and need to be accounted for, as well as any taxes or penalties for disposing of waste. Activities associated with safeguarding fuel depots and security protection for convoys also add to the cost of fuel. The FBCF for Afghanistan varies for each facility and circumstance (U.S. Under Secretary of Defense AT&L, 2009). The Commandant of the Marine Corps, James Conway, in a speech given at the 2009 Navy Energy Forum, stated that “transporting fuel miles into Afghanistan and Iraq along risky and dangerous routes can raise the cost of a $1.04 gallon up to $400” (Chavanne, 2009, para. 3).

Costs associated with providing diesel fuel to ANSF facilities directly competes against other U.S. defense programs (Under Secretary of the Air Force, 2010). The U.S. undersecretary of the Air Force, Erin Conaton, stated at the 2010 USAF Energy Forum:

> This spending pattern is cause for concern. First, we live in a fiscal environment where, at best, the military is looking at a flat topline.

> This means that every dollar we spend on energy is one less dollar we can spend on our Airmen, their readiness, or our weapons systems (U.S. Under Secretary of the Air Force, 2010, para. 8).

As shown earlier, the FBCF for diesel fuel is estimated to be somewhere between $20–$400 per gallon in the Afghanistan region (Chavanne, 2009). At this rate, a diesel generator system becomes a costly solution for powering relatively simple facilities with modest power requirements.

> A 60-kW generator consumes fuel at a rate of 4.5 gallons per hour for an annual total of well over 39,000 gallons. If the price for fuel was only $2.15 per gallon, this single fossil fuel generator would cost in excess of $84,000 annually to operate. Furthermore, there is an additional cost to maintain and repair these generators. Depending on the size and energy demands of the Forward Operating Base, it is conceivable that a single Forward Operating Base could require approximately 5,400 gallons of fuel per 24 hours [costing] just under $5 million annually. (Kuntz, 2007, p. 157)

This inefficiency across all ANSF facilities in Afghanistan has cost the U.S. millions of unnecessary dollars.

Section 1 presented various sources including congressional investigations and excerpts from the NSS concluded that fuel logistics, emissions, and costs are directly contributing to sustained risks to operations security in Afghanistan and U.S. national security.

2. Lack of Alternative Energy Solutions

The USACE does not currently have tools for its civil engineers to optimize various energy solutions when designing or modifying ANSF installations in Afghanistan. The predominant energy solution to power off-grid facilities is via a diesel generator, much like the one pictured in Figure 3 (Defense Science Board, 2010).

Figure 3. Caterpillar Diesel Generator 2260 ekW 2825 kVA 50 Hz 1500 rpm 11000 Volts. (From: Caterpillar, 2010)

The diesel generator provides electricity to run heating, ventilation, and air conditioning (HVAC) units, electricity for computers and radio transmitters, security systems such as surveillance cameras and alarms, charging cell phones, and other basic facility functions (Defense Science Board, 2008). In order to support these system capabilities, a typical operational scenario in Afghanistan requires the diesel generator to run 24 hours per day and seven days a week (Deloitte, 2009). Although the diesel generator solution meets the customer's current needs, it is inefficient and costly (Defense Science Board, 2008). Diesel generators used in Afghanistan operate in either the on or off position therefore they burn the same amount of fuel regardless of the load. In addition, the USACE overestimates power consumption by a minimum of 25% (USACE, 2011). Surplus energy is thus continuously generated and wasted.

The U.S. Army Corps of Engineers (USACE) contributes to the ANSF by "designing and constructing facilities for the Afghan National Army, Afghan National Police and other defense sectors" (USACE, 2011, para. 5). They have constructed more than 100 facilities for the ANP and are working towards completing a total of roughly 700 facilities. One of the major problems is that the DoD currently does not have clear guidance and strong incentives to implement alternative energy solutions (DSB, 2001).

Currently there are no renewable energy power generation standard designs as there are for diesel power generation (USACE, 2011).

Lacking a decision-making process hinders determination of optimal energy solutions that include energy sources other than diesel types. There is thus a need to determine alternative energy systems for ANSF installations. Such a need precipitates the research captured in this thesis.

B. RESEARCH QUESTION

The purpose of this research is to answer this question:

What approach can be developed to aid in determining optimal energy systems for Afghanistan National Security Force installations?

C. RESEARCH APPROACH OVERVIEW

Discussed in detail in Chapter II, the approach to answering the question is broken into three phases: the generation of inputs, the Multi-Attribute Decision-Making for Renewable Energy Solutions (MRES) process, and the generation of an optimal energy rubric. The first phase of the approach generates the inputs to the MRES process: stakeholder needs, energy load profile parameters, and renewable energy parameters. The second phase of the approach, the MRES process, consists of three functions: stakeholder needs mapping, trade space analysis, and optimization. The product of this process permits the third phase of the approach, the generation of a rubric—a tool to quickly determine the optimal energy portfolio for a given location. Each energy portfolio consists of a diesel generator supplemented by a unique combination of solar panels, wind turbines, and batteries.

The inputs are developed from stakeholder needs through pairwise comparisons, the analytic hierarchy process (AHP) (Saaty, 1982), and the full analytical criteria method (Brassard, 1989). An energy load is defined for every hour throughout a 24-hour period. The renewable energy parameters are the hourly solar irradiance and wind speed.

Stakeholder needs mapping uses the quality function deployment (QFD) method (Akao, 1994) to translate the weights from stakeholder needs to weighted system attributes. A trade space analysis is performed using the National Renewable Energy Laboratory's Hybrid Optimization Model for Electric Renewables (HOMER). HOMER receives the renewable energy parameters and the energy load profile as input to conduct thousands of simulations, thoroughly exploring the trade space. Optimization involves scaling all of the possible solutions in the trade space using HOMER's output combinations, using the simple additive weighting (SAW) technique, obtaining a score (as the product of the weighted system attributes developed from QFD and the system metrics from the simulation), and selecting the highest score corresponding to the optimal energy portfolio for a given location (hence, the given environmental conditions).

In the last phase of the approach, the generation of an optimal energy rubric, trade space analysis and optimization are repeated 28 times to identify energy systems that address all combinations of solar irradiance and wind speed for application in Afghanistan. An optimal energy rubric is then generated by organizing the 28 unique and optimized energy system designs for quick energy portfolio decision-making.

D. BENEFITS

The results from applying this approach show that 3 million dollars can be saved per installation over a 25-year period. The USACE still have plans to construct an additional 600 facilities for the ANP alone (USACE, 2011); therefore, if this approach is applied to the remaining USACE construction projects in Afghanistan, $1.8 billion dollars could be saved over the next 25 years.

The economic burden is a critical threat to U.S. national security, and it is therefore critical to explore all opportunities to reduce the cost associated with the war (U.S. National Security Strategy, 2010). The National Security Strategy highlights the risk to U.S. and allied interests and provides justification for seeking alternative methods for powering installations in Afghanistan.

Remaining a fossil fuel burning force and maintaining an economy dependent on fossil fuels will only prolong the U.S.'s involvement with rogue and contentious nations (Kalicki and Goldwyn, 2005). Oil dependency will continue to weaken the U.S. political position (Kalicki and Goldwyn, 2005). However, by leading the world in alternative and renewable energy research and through its implementation of alternative energy sources, the U.S. can reap the benefits from stimulating the domestic economy and strengthening national security through energy stability and independence (U.S. National Security Strategy, 2010).

Simply by cross-referencing solar and wind data for any location in Afghanistan, this approach can tell the engineer the photovoltaic power required, the number of wind turbines required, and the number of batteries required. Not only is this approach suitable for Afghanistan, but also at home and anywhere on the planet.

II. APPROACH

The purpose of this chapter is to describe the functions, components, and processes within an approach that, when applied to Afghanistan, will answer the research question for determining optimal energy systems for ANSF installations. The application of this approach to Afghanistan is discussed in Chapter III.

The core process of the approach utilizes a multi-attribute decision-making (MADM) (Yoon and Hwang, 1995) based process. Energy system decision tools need a MADM process to understand life cycle implications for a variety of energy portfolio decisions as well as ecological and socio-economic variables (Ender, Murphy & Haynes, 2010; Murphy et al., 2010). Ender et al. (2009) advocated:

> The creation of a tool that presents a decision maker with the ability to generate endless hybrid mix scenarios and determine which various renewable and non-renewable energy systems meet annual energy load requirements, acquisition and operation costs, and individual solution attributes. (Ender et al., 2009, p. 1)

The approach is based on Ender's use of the MADM process for energy portfolio decision-making (Ender et al., 2010). The development of the approach involves these modifications to Ender's work:

- Prioritization of stakeholder needs using the full analytical criteria method (Brassard, 1989)
- Inclusion of both initial and life cycle cost in the stakeholder needs
- Utilization of actual solar and wind data
- Inclusion of specific hardware characteristics
- Definition of hourly load profile
- Optimization using the simple additive weighting (SAW) technique

- Generation of an optimal energy rubric containing specific energy system characteristics

The approach has three main phases: input generation, the MRES process, and generation of an optimal energy rubric. The first phase generates the required inputs for the MRES process. There are three components of the input generation phase: stakeholder needs, an energy load profile, and renewable energy parameters.

Stakeholder needs are prioritized by first identifying all of the stakeholders affected and understanding their values and perspectives. Research is required to identify all those affected by energy system implementation and their respective energy system needs. The next step is to prioritize the relative importance of the stakeholders and their needs. Prioritizing the stakeholders is accomplished through pairwise comparisons and the analytic hierarchy process (AHP) (Saaty, 1982). Pairwise comparisons involve comparing each stakeholder against one another and assigning quantitative values indicating their relative importance to each other with respect to energy system implementation. The AHP is used to capture the quantitative values in a matrix, where the values are reduced to vectors of weights that describe the relative importance of each stakeholder. Needs are then extrapolated by analyzing and categorizing common stakeholder values. Needs are also assigned weights based on individual stakeholder's preferences; this step is also accomplished by pairwise comparisons and the AHP. The full analytical criteria method (Brassard, 1989) is used to establish final need weightings by taking the product of the individual stakeholder preferences and the stakeholder weights.

Next, an energy load profile is defined. A specific energy load demand is specified for every hour throughout a 24-hour period. Monthly and annual data are extrapolated by injecting variations into the load such that the average load remains at 60% of the peak load. This extrapolation provides the data to represent an annual cycle.

The last input to the MRES process requires renewable energy parameters be defined using hourly solar irradiance and wind speed data. Since exact solar panel and wind turbine specifications significantly contribute to the accuracy of the solution sets (Newell, 2010), exact hardware specifications are defined. Energy storage is key to enabling renewable energy solutions, thus, exact battery hardware is also defined.

All of the input data supplies the information required for the three core functions of the MRES process: stakeholder needs mapping, trade space analysis, and optimization.

The stakeholder needs mapping function utilizes weights from the stakeholder needs prioritization process to assign weights to key system attributes. A set of eight key system attributes are identified that define the characteristics of energy system designs: total operations and maintenance cost, renewable fraction (the percentage of the system that uses renewable energy production), diesel generator electricity production, solar electricity production, wind electricity production, battery quantity (total batteries used throughout the life cycle), initial capital cost, and life cycle cost. The quality function deployment (QFD) method (Akao, 1994) is used to translate stakeholder needs weights to system attribute weights. Translating the weightings is accomplished by developing numerical values that describe the relationship of the stakeholder needs to the key system attributes. These values are multiplied by the individual stakeholder need weights and these products are summed for each key system attribute in a House of Quality (HOQ) matrix.

Trade space analysis is the second function in the MRES process. The trade space is analyzed by using the National Renewable Energy Laboratory's HOMER simulation software. HOMER conducts thousands of simulations by assembling unique energy system combinations using renewable energy parameters and the energy load profile developed during input generation phase of the approach. During the simulations, energy systems are tested to see if they meet hourly energy load demand throughout the life cycle of the system. Those

energy systems that do meet the load demand are saved in a database, and those energy systems that do not meet the load demand are disregarded.

The last function of the MRES process is optimization. The first step in optimization applies scaling formulas to the energy system metrics from HOMER's simulation database. Scaling permits the energy systems to be compared relative to each other. The second step uses the SAW technique to apply a score by taking the product of the weighted system attributes developed from QFD and the scaled energy system metrics from the simulation. The highest scoring system is the optimized system design for the given environmental conditions.

The last phase of the approach generates an optimal energy rubric. This entails building a matrix listing all regional solar irradiances broken into bands of 0.5 kWh/m^2/day along the left column of the rubric (four bands are required for Afghanistan) and all regional wind classes, one through seven, along the top row of the rubric (seven wind classes are required for Afghanistan). The optimized combinations of energy solutions populate this matrix. They are obtained by conducting the last two functions of the MRES process, the trade space analysis, and system optimization, for all 28 combinations of solar irradiance and wind speeds in a given region. The rubric contains all optimized energy system designs for any given environmental condition for the specified region.

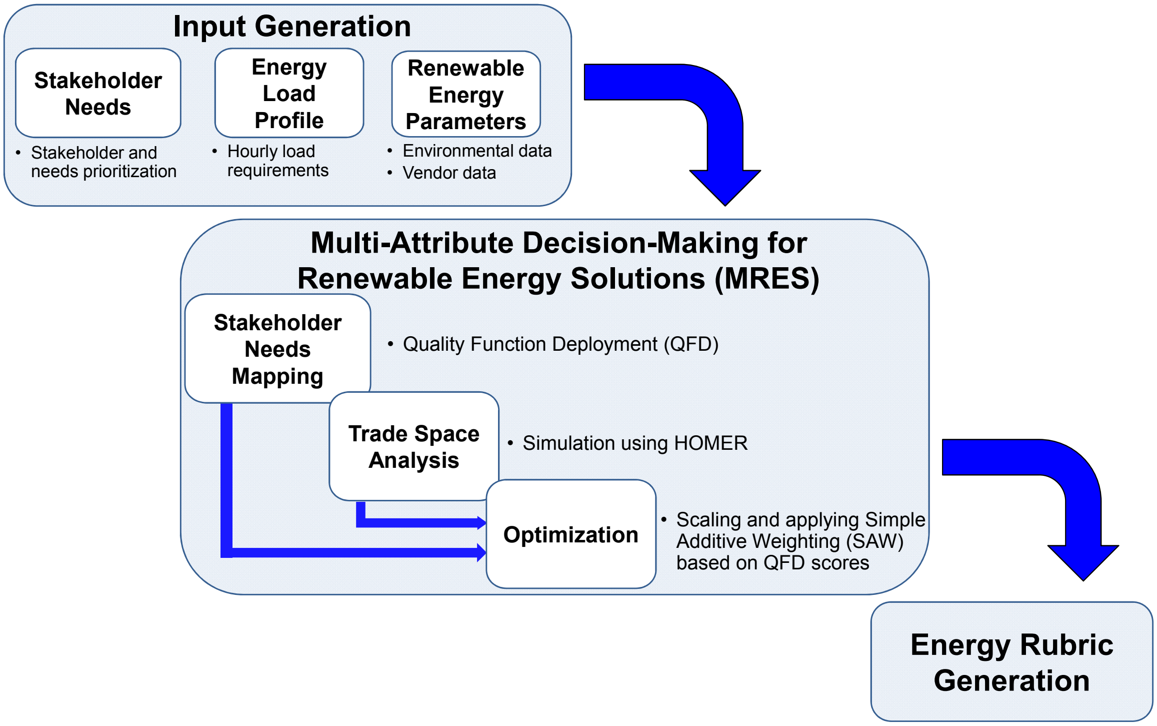

Figure 4. Approach to regional energy system portfolio decision-making.

Figure 4 provides a functional flow of the approach. The three main inputs—stakeholder needs, the energy load profile, and renewable energy parameters—enable the energy MRES process. The output provides the data needed to populate an optimal energy rubric. The rubric provides an engineering tool to quickly determine the optimal energy portfolio for a given location. Each energy portfolio consists of one diesel generator supplemented by a unique combination of solar panels, wind turbines, and batteries.

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III. APPLICATION OF APPROACH

This chapter demonstrates an application of the approach discussed in Chapter II. This chapter also addresses the research question in Chapter I, namely, "*What approach can be developed to aid in determining optimal energy systems for Afghanistan National Security Force installations?",* by applying the approach to energy system optimization for ANSF installations. The optimized energy systems have renewable energy components that complement diesel generators in powering ANSF installations.

The first phase of the approach, the development of the inputs (see Figure 4), is covered in Sections A, B, and C; the second phase, the MRES process, is explained in Section D; and the final phase, optimal energy rubric generation is described in Section E. The results of the application are discussed in Chapter IV.

A. STAKEHOLDER NEEDS PRIORITIZATION PROCESS

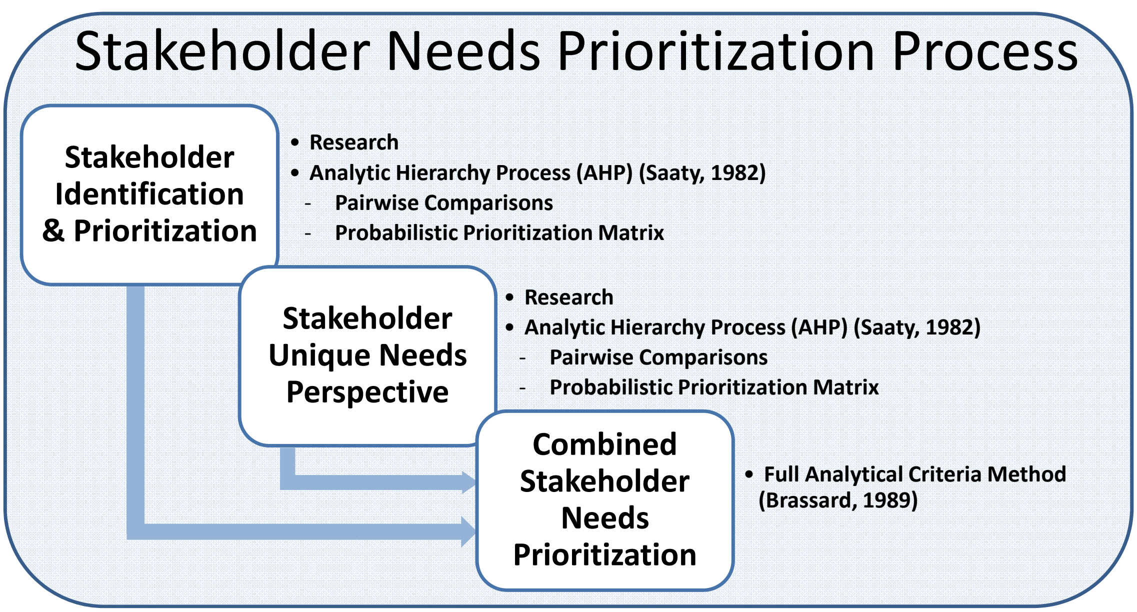

Figure 5. Stakeholder needs prioritization process flow diagram.

Sub-section 1 identifies each stakeholder and concludes by establishing a hierarchy among the stakeholders. In Sub-section 2, individual stakeholder's unique perspectives are discussed and their respective needs are prioritized. Sub-section 3 establishes a hierarchy for all needs across all stakeholders using the full analytical criteria method (see Figure 5).

The stakeholders identified are the Afghanistan government, the International Security Assistance Force (ISAF), the U.S. Army Corps of Engineers (USACE), and the U.S. public.

1. Stakeholder Identification and Prioritization

a. Afghanistan Government

The Afghanistan government is a key stakeholder in energy architecture decisions affecting the ANSF. The Afghanistan government is responsible for the country's overall security, governance, economic growth and poverty (Brummet, 2010). The Afghanistan government published the Afghanistan National Development Strategy (ANDS) in 2008 to highlight the vision for the country. The ANDS states:

> Security will remain the government's highest priority, while the public expenditure programs for investments in energy, water and irrigation, transportation infrastructure, agriculture, agro-based industry, and rural development will remain high priorities, acknowledging the high importance of these sectors for the development of the private sector and for long term and sustainable employment growth. (Nadiri, 2008, p. 58)

The Afghanistan government manages the funding allocated to achieve the national objectives (SIGAR, 2011).

b. International Security Assistance Force

ISAF is the next entity with stake in Afghanistan's energy consumption practices. ISAF's website offers the mission statement of the organization:

> In support of the Government of the Islamic Republic of Afghanistan, ISAF conducts operations in Afghanistan to reduce the capability and will of the insurgency, support the growth in capacity and capability of the Afghan National Security Forces (ANSF), and facilitate improvements in governance and socio-economic development in order to provide a secure environment for sustainable stability that is observable to the population. (ISAF, 2011, para. 1)

The entire force is comprised of 48 troop-contributing nations and totals 132,457 men and women (ISAF, 2011). Figure 6 provides a depiction of the complexity of the ISAF organization.

Figure 6. ISAF Regional Command and Major Units. (From: ISAF, 2011)

ISAF states on its website:

> The main role of ISAF is to assist the Afghan government in the establishment of a secure and stable environment. To this end, ISAF forces conduct security and stability operations throughout the country together with the Afghan National Security Forces and are directly involved in the development of the Afghan National Security

> Forces through mentoring, training and equipping. (ISAF, 2011, para. 2)

ISAF has a critical role because it represents not only the international community of governments, but also the deployed troops in theater who are risking their lives to secure the region, rid the country of terrorists and establish a stable self-regulating government. The website further states:

> Through its Provincial Reconstruction Teams, ISAF supports reconstruction and development (R&D) in Afghanistan, securing areas in which reconstruction work is conducted by other national and international actors. Where appropriate, and in close cooperation and coordination with Afghanistan Government and UNAMA representatives on the ground, ISAF also provides practical support for R&D efforts, as well as support for humanitarian assistance efforts conducted by Afghan government organizations, international organizations, and non-governmental organizations. (ISAF, 2011, para. 3)

There are 48 countries currently assisting Afghanistan in forming a stable government. Each of the countries involved has troops on the ground in dangerous conditions and has contributed significant funding to achieve the objectives set forth by the Afghanistan government. As of 29 July 2011, the Department of Defense reports that 2,702 Afghanistan Coalition service members have lost their lives in support of Operation Enduring Freedom in Afghanistan (Icasualties.org, 2011).

c. U.S. Army Corps of Engineers

The USACE is another organization identified with stake in ANSF's energy solution trade space. The mission of the USACE in Afghanistan, as defined on its website, is to:

> Deliver timely quality infrastructure and services in support of the integrated Afghan National Security Coalition Forces' counter-insurgency (COIN) operations aimed at protecting the population and defeating the Anti-Afghanistan Forces (AAF). On order, provide sustainable development projects for the Afghan people that employ the populace, build skilled human capital, and promote the future stability of Afghanistan. (USACE, 2011, para. 1)

One of the primary tasks of the USACE is to help the Afghan government “build the District’s Sustainable Development Program to include Water, HTRW, Roads, Bridges, Electrical, and other essential service projects” (USACE, 2011, para. 3). The USACE, therefore, needs to identify and implement energy solutions that promote and support the Afghan government with the ability to achieve its energy objectives.

d. U.S. Public

The last stakeholder identified is the U.S. public. Since 2001, the U.S. public has contributed in excess of $1 trillion dollars to Afghanistan (Belasco, 2011). As a result, the U.S. public has been subjected to an additional burden of reduced homeland initiatives (Under Secretary of the Air Force, 2010).

The U.S. public has also lost the lives of its men and women who have deployed to Afghanistan. The U.S. has provided the greatest contribution, sustaining a force of approximately 90,000 troops (ISAF, 2011). Additionally, the U.S. is engaged in the greatest number of regions throughout the country (ISAF, 2011).

e. Prioritization of Stakeholders

The next step uses the pairwise comparison process to determine the stakeholder hierarchy. This exercise yields the corresponding weight or influence of each stakeholder. The purpose of the pairwise comparison is to compare each stakeholder against another until all stakeholders have been compared. The process uses subjective interpretation derived from research to assign a quantitative value. This process is performed for all four stakeholders. The ranking is on a preference scale of 1–9 corresponding to the following qualitative values: 1 for ‘neutral’, 3 for ‘moderately prefer’, 5 for ‘strongly prefer’, 7 for ‘very strongly prefer’, and 9 for ‘extremely prefer’.

Stakeholders																		Stakeholders
U.S. Army Corps of Engineers	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	U.S. Public
U.S. Army Corps of Engineers	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Afghanistan Government
U.S. Army Corps of Engineers	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	International Security Assistance Force
U.S. Public	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Afghanistan Government
U.S. Public	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	International Security Assistance Force
Afghanistan Government	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	International Security Assistance Force

Table 2. Stakeholder pairwise comparisons.

Table 2 contains the results from the pairwise comparison amongst the stakeholders. The quantitative value assigned from each comparison is highlighted in each row. The values are used to calculate the weight of each stakeholder in ANSF's energy solution trade space. By establishing the appropriate weight factor, the right composition of influence is given to each stakeholder.

In Table 2, the U.S. public receives a value of six over the USACE because the U.S. public has the ability to shape the direction of the USACE through voting.

Next, the Afghanistan government receives a value of three over the USACE because the Afghanistan government is a sovereign nation and the USACE is a servicing organization supporting the Afghanistan government's cause (USACE, 2011).

ISAF receives a score of thee over the USACE because ISAF personnel have a higher probability of being affected by the energy decisions. The USACE is a servicing organization and less likely to experience long-term impacts from energy decisions.

Next, the U.S. public and the Afghanistan government are considered equal stakeholders when compared to one another. The rationale is that it is in the U.S. public's interests that the Afghanistan government is independent and capable of sustaining its country without continuous aid from the U.S.

ISAF receives a value of two when compared to the U.S. public. The logic for this score is that the U.S. is just one country involved in the rebuilding effort in Afghanistan and ISAF represents all 48 countries.

The final stakeholder comparison concludes that the Afghanistan government and ISAF are neutral. The rationale used is that ISAF is a complimentary organization to the Afghanistan government and not a subordinate entity. The 48 nations that constitute ISAF can retract any support at their discretion (Nadiri, 2008).

Figure 7 contains the matrix generated from the AHP using inputs from the pairwise comparisons (on the left) and a bar graph comparing the weights to each other (on the right). It shows that ISAF is assigned the largest weight of 34%, the U.S. public and Afghanistan government a weight of 29%, and the USACE a weight of 8%.

Stakeholders

Stakeholder	Stakeholder	U.S. Army Corps of Engineers 1	U.S. Public 2	Afghanistan Government 3	International Security Assistance Force 4	n^{th} root	Weights
U.S. Army Corps of Engineers	1	1	0.17	0.33	0.33	1.32	**0.08**
U.S. Public	2	6	1	1	0.50	1.32	**0.29**
Afghanistan Government	3	3	1	1	1	1.32	**0.29**
International Security Assistance Force	4	3	2	1	1	1.57	**0.34**

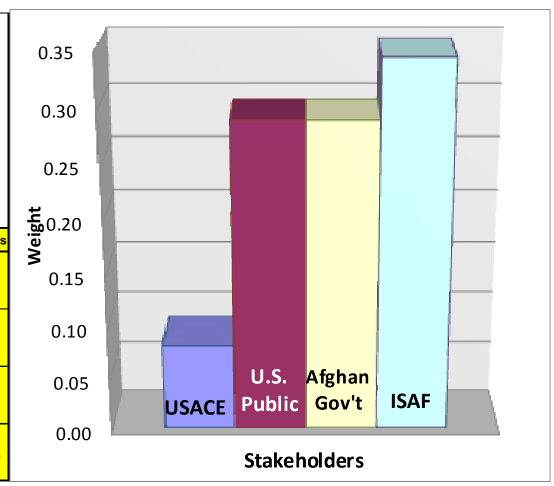

Figure 7. Prioritization of stakeholders.

In Sub-section 2 the unique stakeholder needs are presented and pairwise comparisons are used to establish hierarchies among the needs specific to each stakeholder.

2. Stakeholder Unique Needs Perspective

The purpose of this section is to present the unique needs of each stakeholder and to formulate a hierarchy based on literature research. The values used in the formation of the hierarchy are subjective, but the purpose is to illustrate the approach espoused in this thesis.

a. Afghanistan Government Perspective

The ANDS outlines the Afghanistan government's top priorities, two of which are security and governance (Nadiri, 2008). According to a Delloite study, "energy security and national security are closely interrelated: threats to the former are likely to translate as threats to the latter" (Delloite LLP, 2009, p. 14). As a result, the Afghanistan government is deeply motivated to mitigate any risk to energy security (Nadiri, 2008). As discussed in Chapter I, the security ramifications that arise from diesel fuel convoys increase the risk to ANSF energy stability.

The Afghanistan government is focused first on security (Nadiri, 2008). The ANSF requires energy to perform security functions and energy therefore plays a significant role in establishing and assuring security in the country (Nadiri, 2008). Energy security is measured in how reliable and available power is at specific outlets across the country, in this context, at each ANSF facility. Energy is critical in powering functions such as security and surveillance systems, gates, computer and communications equipment, HVAC systems, etc. (DSB, 2001).

Much of the cost of the energy incurred by Afghanistan is provided by the United States and international community (Nadiri, 2008). The ANDS states that "current estimates for total assistance, official development assistance and security-related expenditures, are $40 to $50 billion" (Nadiri, 2008, p. 155). Eventually the Afghanistan government must become self-sufficient and, therefore, given options in solving its future energy challenges, it prefers low-cost energy solutions that are sustainable.

The bulk of the infrastructure that exists in Afghanistan now is the direct result of U.S. and international partner contributions (Nadiri, 2008). When assessing future costs required to sustain this infrastructure, the ANDS is focused on “the diversification of energy resources for long term low cost energy, energy security and clean energy use” (Nadiri, 2008, p. 77).

The pairwise comparison in Table 3 captures the Afghanistan government’s determined preference in energy system needs. The highlighted values indicate the determined preference of one need versus another. The values are a subjective evaluation of data obtained from literature research of the sources cited herein.

Afghan Government																		
Stakeholder Need																		**Stakeholder Need**
Security	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Impact
Security	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Initial Capital Cost
Security	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Life Cycle Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Initial Capital Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Life Cycle Cost
Initial Capital Cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Life Cycle Cost

Table 3. Afghanistan government pairwise comparison.

Security, the Afghanistan government’s top objective and therefore the most important of the needs, earns a seven over environmental impact. Security earns a six over initial capital cost because of the main focus of the government securing peace in the country. The Afghanistan government operates largely on contributions from foreign aid and therefore does not prioritize cost (SIGAR, 2011). Likewise, security ranks higher than the need for low life cycle cost.

Initial capital cost receives a higher priority than environmental impact, based on the assumption that environmental considerations in Afghanistan to date have not been substantial and the Afghanistan government is more likely to contribute funding for energy than to implement aggressive energy conservation initiatives (Nadiri, 2008).

Additionally, life cycle cost ranks slightly higher than environmental impact. The Afghanistan government is likely to face a transition point where the foreign aid will decrease and the sustainment of energy systems will require internal funding in the next five to ten years (SIGAR, 2011).

Finally, initial capital cost and life cycle cost are evaluated as equal in priority, considering that Afghanistan does not pay the majority of the costs at this point (SIGAR. 2011). Figure 8 displays Afghanistan government's concerns. Security ranks first overall with a weight of 65%, followed by initial cost and life cycle cost at 14%, and environmental impact at 7%.

Afghan Government	Concerns	Security	Environmental Impact (Attribute: Renewable Energy)	Initial Cost	Life Cycle Cost		
Concerns		1	2	3	4	n^{th} root	Weights
Security (Attributes: Logistics & Sustainment Overhead – fuel convoys, maintenance convoys, spares, energy independence)	1	1	7	6	5	3.81	**0.65**
Environmental Impact (Attribute: Renewable Energy)	2	0.14	1	0.33	0.50	0.39	**0.07**
Initial Cost	3	0.17	3	1	1.00	0.84	**0.14**
Life Cycle Cost	4	0.20	2	1	1	0.80	**0.14**

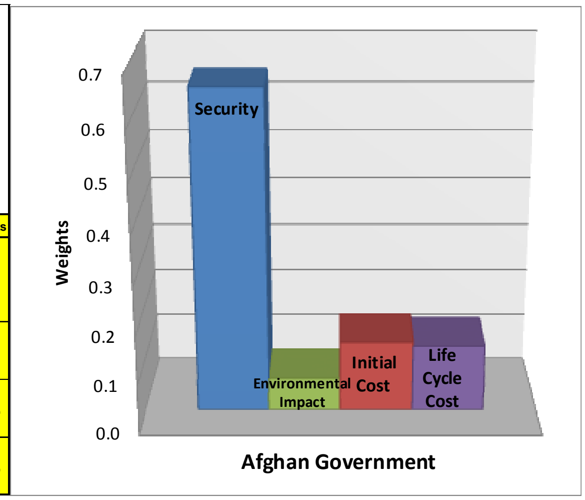

Figure 8. Prioritization of needs for the Afghan government.

b. ISAF Perspective

ISAF's primary role is to support the Afghanistan government in increasing and sustaining security (ISAF, 2011). ISAF represents the 48 countries that have pledged troops and/or funding to aid Afghanistan in the rebuilding efforts. From this perspective, the ISAF's primary need is to establish security in the country. Energy is a vital contributing factor to ensuring the security in the region and is, therefore, at the forefront of ISAF's concerns (Lovins, 2010).

Low initial cost is the next need. ISAF is an international organization, operating on the contributions of its member countries (ISAF,

2011). The member countries' war effort in Afghanistan compete for resources (money) with its domestic priorities. Collectively, ISAF seeks lowest initial cost solutions for energy that meet the load demand.

Life cycle cost is also important. It accounts for the operations and maintenance cost of energy solutions. The countries that provide funding and support to Afghanistan now will most likely not fund Afghanistan efforts forever (Nadiri, 2008). As a result, low life cycle cost solutions are preferred as this increases the probability that the Afghanistan government will be able to sustain operations upon termination of foreign aid (Nadiri, 2008).

Environmental impact must be addressed. The ANDS specifically calls for energy solutions that consider the environment in the design (Nadiri, 2008) Further, ISAF is accountable to the respective civilian governments and populations on all issues including the environment (DSB, 2008). Most of the 48 countries comprising ISAF also lead the world in environmental conservation initiatives (DSB, 2008). The environment is an important consideration across this community and should be included in energy decisions.

International Security Assistance Force																		
Stakeholder Need																		**Stakeholder Need**
Security	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Impact
Security	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Initial Capital Cost
Security	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Life Cycle Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Initial Capital Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Life Cycle Cost
Initial Capital Cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Life Cycle Cost

Table 4. ISAF pairwise comparison.

ISAF's number one priority is to establish and maintain security in Afghanistan (ISAF, 2011). Security receives a nine when compared to environmental impact (Table 4). This indicates that security is the most important need and environmental impact is the least critical need. Security is preferred to initial capital cost and receives a value of seven. Security is also preferred to life cycle cost and receives a value of six. Articles on ISAF's website are primarily associated with enhancing security and stability in Afghanistan. Cost initiatives

and environmental impacts are not directly considered (ISAF, 2011). Consequently, ISAF weighs security impacts as the highest priority need, followed by costs and then the environmental impact.

Environmental regulation is a need outlined in the ANDS but is ranked behind security, cost, affordability and sustainability. Therefore, initial capital cost and life cycle cost receive values of five and four, respectively, over the environmental impact.

The overall weight allocations applied to the four significant needs are included in Figure 9. Security dominates all of the needs and accounts for 68% of the total weight. Initial cost and life cycle cost rank second at 14%. The remaining 4% is applied to environmental impact.

International Security Assistance Force	Concerns	Security	Environmental Impact (Attribute: Renewable Energy)	Initial Cost	Life Cycle Cost		
Concerns		1	2	3	4	n^{th} root	**Weights**
Security (Attributes: Logistics & Sustainment Overhead – fuel convoys, maintenance convoys, spares, energy independence)	1	1	9	7	6	4.41	**0.68**
Environmental Impact (Attribute: Renewable Energy)	2	0.11	1	0.20	0.25	0.27	**0.04**
Initial Cost	3	0.14	5	1	1	0.92	**0.14**
Life Cycle Cost	4	0.17	4	1	1	0.90	**0.14**

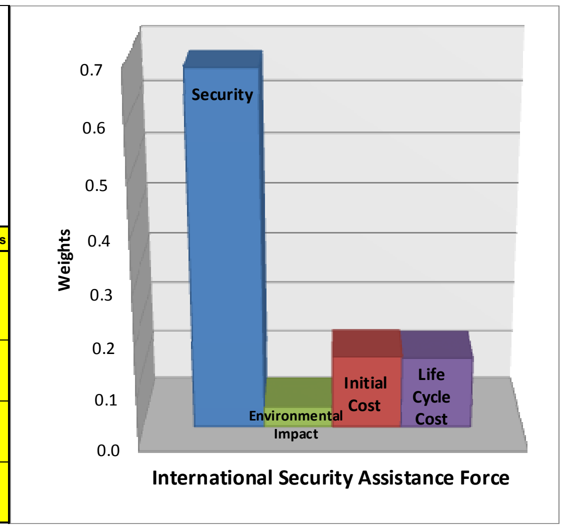

Figure 9. Prioritization of needs for ISAF.

c. U.S. Army Corps of Engineers Perspective

The USACE, like ISAF, has interests similar to those of the Afghanistan government. Security is the USACE's top priority in designing energy solutions (USACE, 2011).

Initial cost is another need to consider. The USACE highlights sustainable development projects in Afghanistan as a main objective of the organization (USACE, 2011). This translates to implementing solutions that are

affordable and sustainable. The ANDS specifically addresses the fact that only energy solutions that can be autonomously sustained by the Afghanistan government should be implemented (Nadiri, 2008).

Finally, the USACE is also concerned with environmental impacts. The USACE, accountable to higher organizations within the U.S. government, is ultimately accountable to the U.S. public. Based on the position the U.S. holds in energy conservation initiatives, the USACE should only implement energy solutions that comply with standards in the U.S.

The USACE ranks last in the pairwise comparison of the stakeholders and has a priority and weight allocation of 8%. Although the weight is minimal, the USACE has a substantial role in the execution of the rebuilding efforts in Afghanistan supporting the ANSF (USACE, 2011). Table 5 shows the results of the pairwise comparison of the stakeholder needs from the USACE perspective.

USACE																		
Stakeholder Need																		**Stakeholder Need**
Security	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Impact
Security	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Initial Capital Cost
Security	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Life Cycle Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	Initial Capital Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Life Cycle Cost
Initial Capital Cost	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Life Cycle Cost

Table 5. USACE pairwise comparison.

Security received a seven over environmental impact, establishing that security is the dominant need over the environment. The USACE's top priority in Afghanistan is to assist the Afghan government in establishing the ANSF, capable of mitigating threats to security in the country both now and in the future (USACE, 2011).

Initial capital cost dominates security, therefore, it receives a value of five. The justification behind this value is that the USACE must balance competing projects against diminishing funding levels, thus, increasing the

priority for low initial capital cost. The USACE is assumed to look for cheaper solutions to meet the objectives.

Life cycle cost only slightly out-weighs security from the USACE perspective. The justification for this is that energy solutions need to be sustainable since ownership is transferred to the Afghanistan government. Initial capital cost strongly out-weighs the environmental impact for energy solutions, thus indicating that immediate cost savings are the primary objectives for the USACE.

Life cycle cost dominates the environmental impact but to a lesser degree than compared to initial capital cost. Initial capital cost significantly dominates life cycle cost. Construction funds and operations and maintenance funds come from different funding sources. The overall costs of energy systems are not a primary concern for the USACE. The organization focuses primarily on establishing a viable ANSF. The overall cost of establishing the ANSF is not a primary decision variable. The USACE is primarily concerned with initial cost.

Figure 10 displays the concerns and corresponding weights identified for the USACE. The weights identified for the concerns are as follows: Initial cost ranks the highest with 64%, life cycle cost at 17%, followed by security at 15%, and environmental impact at 4%.

U.S. Army Corps of Engineers	**Concerns**	**Security**	**Environmental Impact (Attribute: Renewable Energy)**	**Initial Cost**	**Life Cycle Cost**		
Concerns		1	2	3	4	n^{th} root	**Weights**
Security (Attributes: Logistics & Sustainment Overhead – fuel convoys, maintenance convoys, spares, energy	1	1	7	0.20	0.50	0.91	**0.15**
Environmental Impact (Attribute: Renewable Energy)	2	0.14	1	0.14	0.25	0.27	**0.04**
Initial Cost	3	5	7	1	7	3.96	**0.64**
Life Cycle Cost	4	2	4	0.14	1	1.03	**0.17**

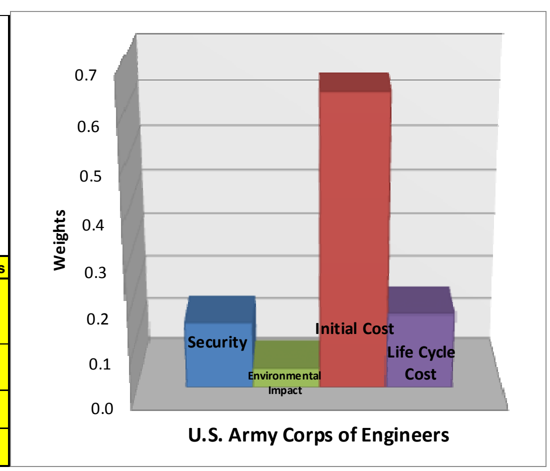

Figure 10. Prioritization of needs for USACE.

d. U.S. Public Perspective

The U.S. public's primary need in the context of the war in Afghanistan and the corresponding energy posture are to promote security and stability. The rationale used is that energy is a security enabler and the more stable and reliable the Afghanistan Government becomes at self-regulating the quicker the U.S. can withdrawal troops. Further, the quicker the transition of Afghanistan to an autonomous state is, the less funding the U.S. will have to commit to support their efforts.

The U.S. public bears the burden of the U.S. costs expended in support of the war in Afghanistan and the cost of energy. Lowering costs attributed to energy in Afghanistan translates to cost savings that can be applied to domestic priorities or used to reduce the national debt. Therefore, a critical need of the U.S. public is low-cost energy initiatives in Afghanistan.

The last major need of the U.S. public is the consideration of the environmental impact of energy solutions.

The U.S. public ranks second among the four key stakeholders in terms of influence and weight. Table 6 captures the results of the pairwise comparison of the top energy system needs from the U.S. public's perspective.

U.S. Public																		
Stakeholder Need																		**Stakeholder Need**
Security	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Impact
Security	9	8	7	6	5	**4**	3	2	1	2	3	4	5	6	7	8	9	Initial Capital Cost
Security	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Life Cycle Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Initial Capital Cost
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	Life Cycle Cost
Initial Capital Cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Life Cycle Cost

Table 6. U.S. public pairwise comparison.

Security receives a seven over environmental impact, reinforcing the U.S. values of security as a higher priority.

Security dominates initial capital cost and receives a value of four. The energy solution in Afghanistan seeks to meet security considerations over cost of the energy system. In other words, if an energy system costs more up

front to increase or obtain higher levels of security in the region, the U.S. values that system and is willing to accept the increased cost.

Security also dominates life cycle cost. The assumption is that the U.S. public values long-term improvements in security over the total life cycle cost of an energy system.

Initial capital cost ranks higher than the environmental impact of a potential energy system, as the average U.S. citizen is assumed to be more concerned with the cost of the war than with the environmental impact.

Life cycle cost ranks higher than environmental impact. The U.S. public generally ranks the cost of the war in Afghanistan as more critical than any impact on the environment.

The overall weight scheme attributed to the four needs is identified in Figure 11.

U.S. Public	Concerns	Security	Environmental Impact (Attribute: Renewable Energy)	Initial Cost	Life Cycle Cost		
Concerns		1	2	3	4	n^{th} root	**Weights**
Security (Attributes: Logistics & Sustainment Overhead -- fuel convoys, maintenance convoys, spares, energy independence)	1	1	7	4	6	3.60	**0.61**
Environmental Impact (Attribute: Renewable Energy)	2	0.14	1	0.25	0.17	0.28	**0.05**
Initial Cost	3	0.25	4	1	1.00	1.00	**0.17**
Life Cycle Cost	4	0.17	6	1	1	1.00	**0.17**

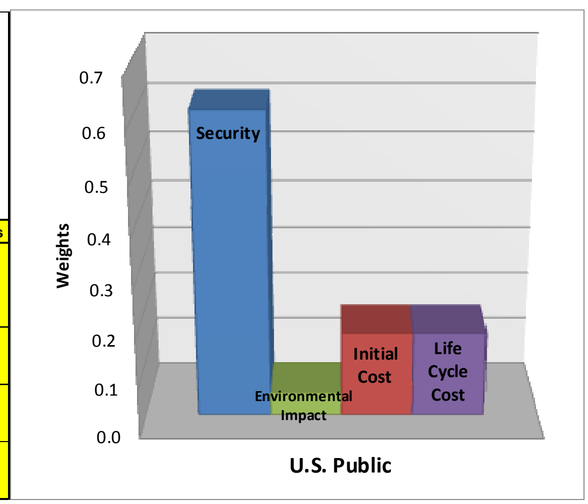

Figure 11. Prioritization of needs for the U.S. public.

Security tops the list, earning 61% of the weight distribution followed by life cycle and initial cost at 17%, and environmental impact at 5%.

In this section, the stakeholders are analyzed to determine the unique basis for their needs. The intent is to assess the justification for each need, thereby proving that security, initial cost, capital cost, and environmental

impact are the main needs of each stakeholder. In Sub-section 3, the stakeholder's needs are compared pairwise to establish a hierarchy in order to ultimately determine the overarching weight of each stakeholder and need that shape the design considerations for energy solutions.

3. Combined Stakeholder Needs Prioritization

Table 7 contains the results from the integration of stakeholder weights and the weights of their individual needs. For instance, the USACE's weight is 0.081 and their security need weight is 0.15 (from Figure 10). The product of the two values equals 0.012, corresponding to the first cell in the matrix under security. The entire stakeholder row is calculated similarly for each need. The need columns are then summed beneath the matrix, producing four need weights.

		Security	*Enviro*	*Cost*		
Stakeholders	*Weights*	**Security**	**Environment**	**Initial Cost**	**Life Cycle Cost**	
U.S. Army Corps of Engineers	0.081	**0.012**	**0.003**	**0.052**	**0.014**	
U.S. Public	0.288	**0.177**	**0.014**	**0.049**	**0.049**	
Afghanistan Government	0.288	**0.188**	**0.019**	**0.042**	**0.039**	
International Security Assistance Force	0.343	**0.232**	**0.014**	**0.048**	**0.048**	
Check Sum	1.00					
						Check Sum
Weighted Performance		**0.609**	**0.051**	**0.191**	**0.149**	1.0

Table 7. Full analytical criteria method (Brassard, 1989) to prioritize combined stakeholder needs.

Figure 12 provides a visual reference to the magnitude of each need weight. Security dominates all other needs, and initial cost is slightly higher than life cycle cost. The environmental need has the lowest weight.

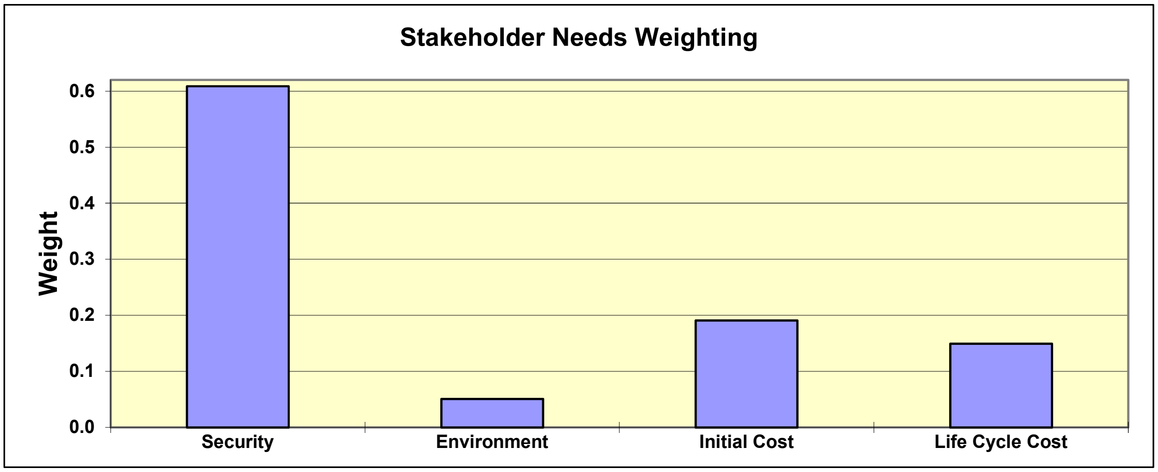

Figure 12. Stakeholder needs weighting.

B. ENERGY LOAD PROFILE DEFINITION

The second input to the MRES process requires generating an hourly load profile to represent energy usage at an ANSF facility. The load profile defines the size of energy system required to provide power for the facility.

1. Experimental Forward Operating Base

Hourly load data is not available for police stations or army bases in Afghanistan. As a substitute for this information, the hourly load data for the Marine Corps' Experimental Forward Operating Base (ExFOB) is used. This data provides the hourly load profile to sufficiently represent smaller ANSF installations. Figure 13 illustrates ExFOB's hourly load profile as defined by Newell (Newell, 2010).

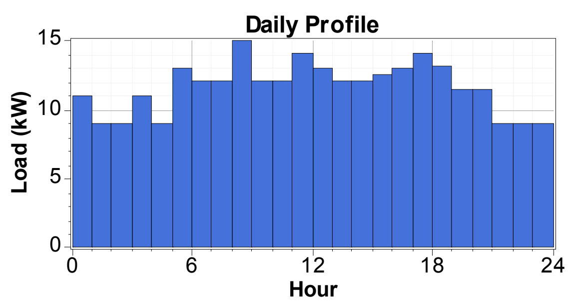

Figure 13. ExFOB hourly load profile as input to HOMER simulation software. (From: NREL, 2011)

HOMER software can introduce random variability to create daily and hourly changes to simulate one year of data. ANP station blueprints use a 60% heuristic to estimate typical demand of the maximum possible load (USACE, 2007). Therefore, daily and hourly random variability is injected into the ExFOB profile to create an average load that is 60% of the peak load. The peak load is thus 19.3 kW, the average instantaneous load is 11.6 kW, and the average daily load is 278 kW. To put this in perspective, an average residential home in the U.S. consumes about 30 kWh per day (U.S. Energy Information Administration, 2011). Therefore, an average daily load of 278 kWh per day equates to roughly nine U.S. residential homes.

C. DEFINITION OF RENEWABLE ENERGY PARAMETERS

Renewable energy parameters make up the third input to the MRES process (see Figure 4). This section defines solar irradiance (Sub-section 1), wind potential (Sub-section 2), and energy storage inputs (Sub-section 3). The inputs defined in Sections B and C feed directly to the National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewables (HOMER) software. This software provides the simulation required to develop the solution trade space. The simulation is discussed in detail in Section D, Sub-section 2, in Trade Space Analysis.

1. Solar Irradiance

The National Renewable Energy Laboratory has developed a Geospatial Toolkit (Figure 14), a software add-in to HOMER.

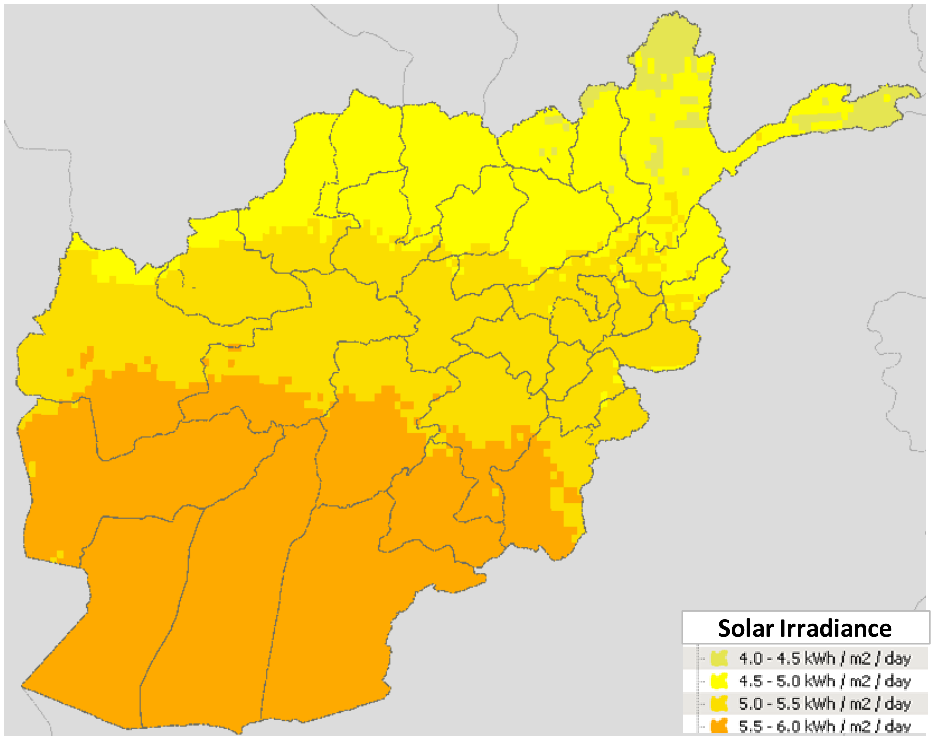

Figure 14. Solar irradiance map of Afghanistan. (From: NREL, 2011)

NREL's Geospatial Toolkit provides detailed solar irradiance source data that can be retrieved by selecting a location on a map. The source data contains hourly solar irradiance data for an entire year for any location selected. The toolkit uses colors to depict annual irradiance averages. For Afghanistan, these averages are broken into four distinct 0.5 kWh/m^2/day bands, as shown in Figure 14. All locations in Afghanistan fall within one of these bands. This work employs the four specific annual averages to represent the four bands, as shown in Table 8.

	kWh/m²/day	Annual Average
s1	4-4.5	4.25
s2	4.5-5	4.75
s3	5-5.5	5.25
s4	5.5-6	5.75

Table 8. Four distinct solar irradiance bands.

These annual averages representing hourly annual data are inputs to HOMER simulation software. These averages also make up the first column for the optimal energy rubric.

The monthly and hourly solar profile used to represent each of the four bands in Table 8 is based on a location in Afghanistan with exactly 5.75 kWh/m^2/day energy potential. This same solar profile is then scaled down to represent bands s3, s2, and s1.

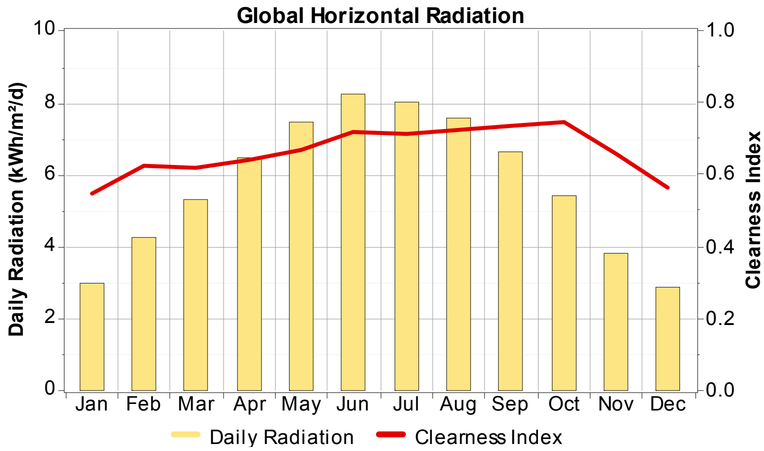

Figure 15. Monthly solar irradiance profile for 5.75 kWh/m^2/day. (From: NREL, 2011)

In Figure 15, the bars represent monthly variations in solar irradiance. Since clouds obstruct solar irradiance, a clearness index is used to measure the average atmospheric clearness. The vertical axis on the right indicates the clearness index. The horizontal line corresponds to this value on this axis and

constrains the maximum amount of solar irradiance that can be accounted for in the HOMER simulation.

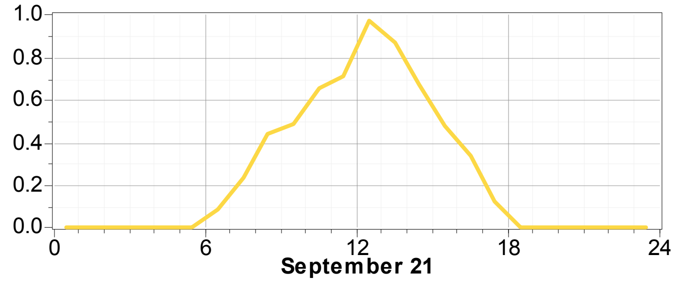

Figure 16. Hourly solar irradiance profile for 5.75 kWh/m^2/day. (From: NREL, 2011)

The data in Figure 16 provides a scaled index of solar irradiance expected on September 21st. Solar irradiance beings at around 0550 hours, and its intensity increases and peaks at 1230 and then decreases until 1830 hours. This hourly data is necessary for the HOMER simulation to accurately assess the performance of renewable energy solutions.

a. Solar Cell Definition

To further maximize the accuracy of the HOMER simulation, specific solar panel hardware is identified. A product search found the best value for photovoltaic panels available. Up-to-date performance values and price permit the most realistic cost and power data.

Manufacturer	Solar Panel System	Maximum Power (KW)	Capital Cost	Cost/kw	Lifetime
Solar World	SW240 Mono	0.24	$ 624.00	$ 2,600.00	25 year linear performance
Solar World	SW 245 Mono	0.179	$ 645.00	$ 3,603.35	25 year linear performance
SHARP	Sharp 80 NE-80EJEA	0.08	$ 400.00	$ 5,000.00	25 year limited warranty on power output
SHARP	Sharp ND 224UC1 Solar Panel	0.224	$ 520.00	$ 2,321.43	25 year limited warranty on power output
SHARP	Sharp NU-U235F1 Solar Panel	0.235	$ 650.00	$ 2,765.96	25 year limited warranty on power output
SHARP	Sharp NU-U240F1 Solar Panel	0.24	$ 630.00	$ 2,625.00	25 year limited warranty on power output
SOLON	Solar Blue 225/01 module	0.225	$ 620.00	$ 2,755.56	10 year product guarantee, 25 year, 5 stage performance
SOLON	Solar Blue 230/01 3BB	0.23	$ 621.00	$ 2,700.00	10 year product guarantee, 25 year, 5 stage performance

Table 9. Sample product search criteria.

Table 9 illustrates the criteria used to select a solar panel. The Sharp ND 224UC1 solar panel (shown in Figure 17) is selected based on the lowest cost per kilowatt at $2,321. The lifespan of all solar panels researched is rated at 25 years.

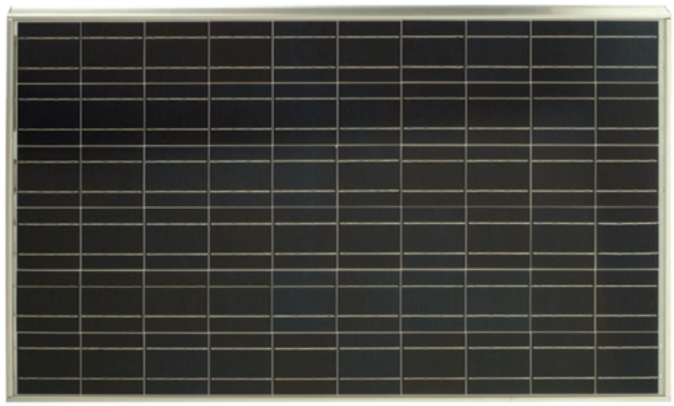

Figure 17. Sharp ND-224UC1 solar panel. (From: Sharp, 2011)

HOMER can accurately simulate solar panel hardware if the simulation accounts for errors introduced by the vendor stated derating factor, temperature effects, and solar irradiance data (Newell, 2010).

Derating accounts for the difference between the maximum power level possible under ideal conditions and the likely power value achieved under deployed realistic conditions. The derating value is a scaling factor that is applied to the power output. In (Newell, 2010), on average, a 54% derating value is reported, temperature effects introduce a 6% error, and irradiance data presents an additional 3.6% error. In this thesis, to account for all of these errors, a derating factor of 44.4% is applied to the Sharp ND 224UC1 solar panel.

Other input parameters required for the HOMER simulation are slope and azimuth of the solar panel, and ground reflectance. A 36.3° slope is commensurate with Afghanistan's latitudinal location on the globe. The selected panels are fixed; thus, they do not track the sun. A zero-degree azimuth is used to describe a panel angled due south. Ground reflectance of 20% is selected as a conservative value but could be as high as 70% from snow-covered ground

(Lambert, 2009). The values of photovoltaic power (in kilowatts) to consider are 0, 10, 50, 100, 150, 200, 250, and 300. The zero-kilowatt value corresponds to energy system combinations that do not include solar production.

2. Wind Potential

An analysis conducted by South Asia Regional Initiative (SARI) for Energy Cooperation and Development indicates that 12% of Afghanistan's total land area is of wind class three or better. The analysis notes that this potential is good for off-grid wind/diesel applications (Elliott, 2011). However, the results in Chapter IV show that even class-one winds prove useful for ANSF size applications.

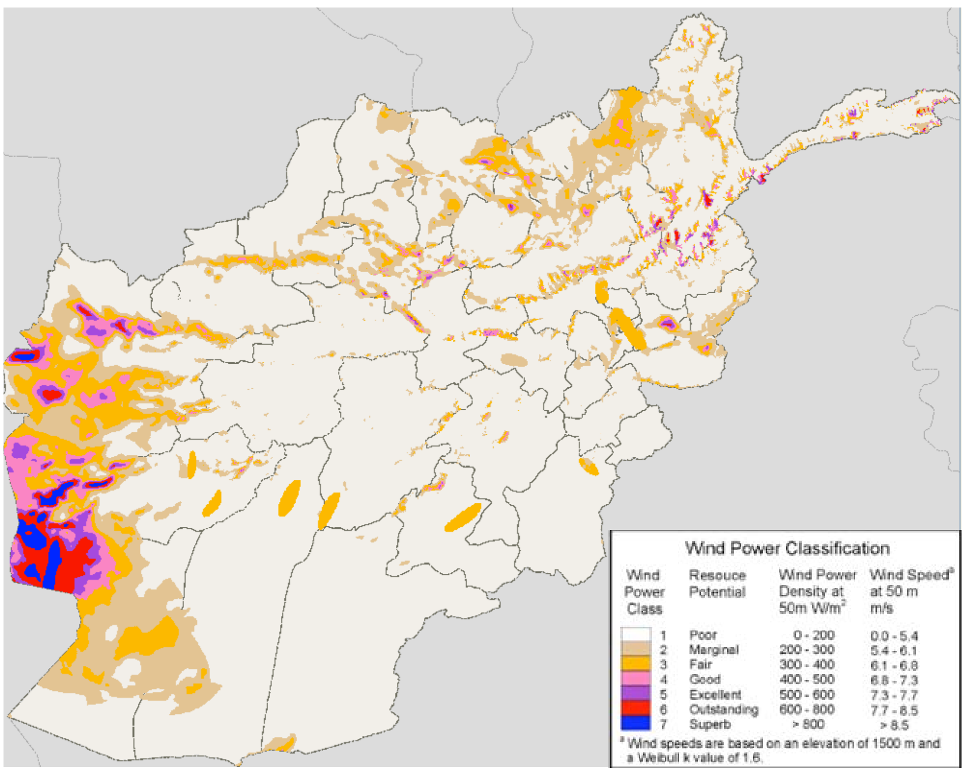

Figure 18. Wind power potential in Afghanistan. (From: NREL, 2011)

In addition to solar data, the Geospatial Toolkit also provides wind energy source data. Figure 18 shows the wind resource available throughout Afghanistan. The Geospatial Toolkit breaks down the wind classes into seven color-coded wind classes.

HOMER can scale wind resource data based on the annual average wind speed (in meters per second). To determine specific input values for the simulation, random sampling is accomplished for each wind class throughout the region using the Geospatial Toolkit's graphical user interface. A total of 30 random samples are taken throughout Afghanistan, with 12 samples used to determine the annual average for wind class 1, which is the most common throughout the region. For all other wind classes, three sampling locations are used.

The annual wind speed averages obtained from random samples are summarized in Table 10. The column on the left shows all of the wind classes 1 through 7. The middle column contains the wind power potential (in watts) that could be harvested at 50 meters above the ground, in a one meter square region of space. The column on the right indicates the annual average wind speed (in meters per second) that is selected to represent the corresponding wind class in the HOMER simulation.

Wind Class	W/m^2 at 50m	Annual Average Wind Speed m/sec
w1	0 - 200	4.28
w2	200 - 300	5.97
w3	300 - 400	6.73
w4	400 - 500	7.48
w5	500 - 600	7.55
w6	600 - 800	7.85
w7	> 800	8.59

Table 10. Annual averages representing seven wind speed categories.

For a simulation at a single location, HOMER fits a Weibull distribution to the wind speed data, and the shape of that distribution is assigned the constant,

k (Lambert, 2009). To represent all seven wind classes in the simulation, one representative wind profile is selected and scaled. A k-value is assigned by averaging the k-values for all 30 random samples. Figure 19 shows annual average wind speeds and k-values for all 30 random samples and indicates an average k-value of 1.7. This value is assigned to the wind profile for the simulation.

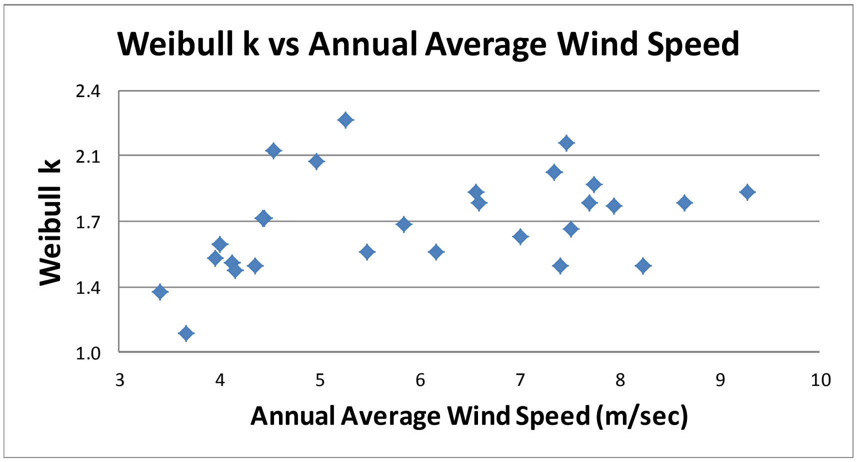

Figure 19. Weibull k values and their corresponding wind speeds.

Figure 20 shows hourly wind speed data during a 24-hour period. This waveform is used to scale and represent all seven wind classes.

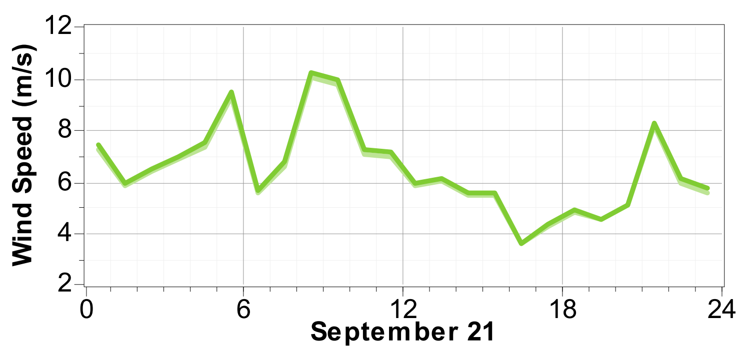

Figure 20. Representative hourly wind speed profile throughout a 24-hour period. (From: NREL, 2011)

Figure 21 illustrates the wind profile for the representative waveform. The profile is for a surface roughness length of 10 millimeters, equivalent to a rough pasture. Since Afghanistan does not have many trees or large infrastructure to

obstruct the wind flow, this represents most of Afghanistan; however; not all locations in Afghanistan will match this wind profile.

NREL's Geospatial Toolkit provides wind data at 50 meters, a commonly used height for wind speed measurement. Unfortunately, a 50-meter tall wind turbine does not fit a solution that is easily implementable in Afghanistan.

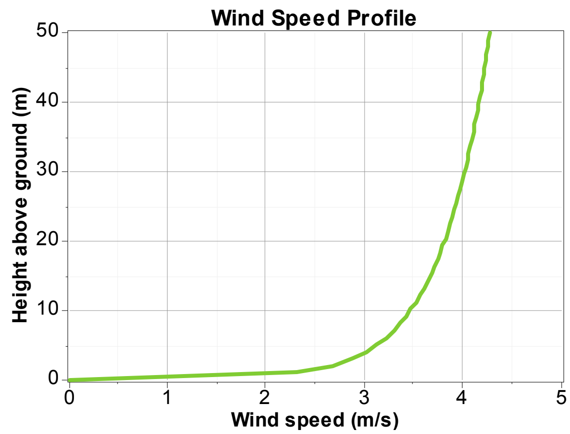

Figure 21. Wind speed profile for representative waveform. (From: NREL, 2011)

A 10-meter tall wind turbine, however, permits a height that is more easily implementable in Afghanistan and is also a commonly referenced height for wind energy extraction (see Table 11).

Wind Power Class*	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m²)	Speed(b) m/s (mph)	Wind Power Density (W/m²)	Speed(b) m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

Table 11. Wind power classes and speeds. (From: Elliott et al., 1986)

The roof of a single story building would provide enough height to achieve a 10-meter hub height implementation. Figure 21 illustrates that a decrease from 50 meters to 10 meters in hub height means an 18% drop in wind speed. The

wind speed profile in Figure 21 permits the user to simulate hub heights other than 50 meters. HOMER uses this curve to determine the energy potential for any given wind turbine hub height.

a. *Wind Turbine Definition*

To maximize the fidelity of the HOMER simulation, a product search found the most current and the best value of wind turbines from available data. This data permits the most realistic cost and power data.

Manufacturer	Maximum Power (KW) under STC	Capital Cost	Tower	Output (DC/AC)	Lifetime	Hub Height (meters)
BWC	60-150 AC KW/hrs/month	$ 7,010.00		24VDC		20m tilt-up tower
ENERCON	330 kW					37
GE	1.6 - 82.5 Wind turbine				20	
Norther Power	100 kw			480VAC	20	37
Southwest Whisper 100	900 watts at 28 mph (12.5 m/s) & 100 kWh/mo at 12 mph (5.4 m/s)	$2,567 land version with turbine and controller	tower 24--$504, 30 $859, 50ft $1225, 65 ft 1,425, 80 ft 1,995	12, 24, 36 or 48 VDC	20 (5 year warranty)	42 or 70 feet
Southwest Whisper 200	1000 watts at 26 mph (11.6 m/s) & 200 kWh/mo at 12 mph (5.4 m/s)	$3405 land version with turbine and controller	tower 24--$504, 30 $859, 50ft $1225, 65 ft 1,425, 80 ft 1,995	24, 36, 48 VDC (high voltage avail)		42 or 70 feet
Southwest Whisper 500	3000 watts at 24 mph (10.5 m/s) Peak Power 3200 watts at 27 mph (12 m/s)	$8795 land version with turbine and controller	30ft $1358, 42ft $1556, 70ft $1991	24, 36, 48 VDC (high voltage avail)		42 or 70 feet

Table 12. Sample product search criteria.

Table 12 indicates that the Southwest Windpower's Whisper 100 is selected, since it provides the best value for the size of load, simple design, and quiet operation. Since the desired application is for smaller installations, a hub height of 30 ft (~10 m) is selected. The total cost of one wind turbine and tower is $3,426.

Figure 22. Southwest Windpower's Whisper 100. (From: Southwest Windpower, 2011)

The Whisper 100, shown in Figure 22, provides a compact design, a 20-year lifetime and the lowest cost. It is touted by Southwest Windpower as, "one of the quietest turbines ever tested by the National Renewable Energy Labs."

Quantities of wind turbines to consider are 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 35, 40, 45, 50, 55, and 60. The zero value corresponds to energy system combinations that do not include wind turbines.

Operations and maintenance costs are averaged as input to HOMER for simulation. Wind measurement international, (http://www.windmeasurementinternational.com/wind-turbines/om-turbines.php), a company that provides wind monitoring and consulting, states, "for modern machines the estimated maintenance costs are in the range of 1.5% to 2% of the original investment per annum" (Wind Measurement International, 2011, para. 4). Therefore, the operations and maintenance cost at 1.5% of $3,426 is $51.39 per year and 2% of $3,426 is $68.52 per year.

Another method of calculating operations and maintenance cost is described in *wind energy the facts.org* (http://www.wind-energy-the-

facts.org/en/part-3-economics-of-wind-power/chapter-1-cost-of-on-land-wind-power/operation-and-maintenance-costs-of-wind-generated-power.html). The specific guidance states:

> O&M costs may easily make up 20–25% of the total levelised cost per kWh produced over the lifetime of the turbine. If the turbine is fairly new, the share may only be 10–15%, but this may increase to at least 20–35% by the end of the turbine's lifetime. (Wind Energy The Facts, 2011, para. 1)

Table 13 breaks down the energy system cost per kilowatt over the lifetime of the system and arrives at an annual O&M cost of $45.68 using the method quoted above. This value represents 20% of the total cost per kilowatt produced over the energy system's lifetime.

$3,426.00	System Cost
100	kWh/month
1,200	kWh/yr
18,000	kWh/lifetime (15 yr)
$0.19	Cost per kWh
$0.04	O&M = 20% of Cost per kWh
$685.20	Lifetime O&M Costs
$45.68	**Annual O&M Costs**

Table 13. O&M as a percentage of cost per kilowatt.

Table 14 summarizes three estimated operations and maintenance values. The average of these three values, $55, is the annual operations and maintenance cost for the Whisper 100 wind turbine in the HOMER simulation.

Maintenance costs as a percentage	
2% of original investment	$68.52
1.5% of original investment	$51.39
20% of kWh produced over lifetime	$45.68
Average	**$55**

Table 14. O&M cost calculated for the Whisper 100.

3. Energy Storage

Accurate energy storage data improves the fidelity of the HOMER simulation. A specific battery is selected to meet the intended application, in this case, an ANSF installation in Afghanistan with an energy load profile of the ExFOB at 278 kWh/day. Therefore, rugged technology and ample capacity are required in a battery.

Absorbed glass mat (AGM) battery technology is especially suitable for the intended environment. AGM batteries, unlike lead-acid, do not require water and are completely sealed (Surrette, 2011). AGM batteries do not contain liquid that can freeze or expand, and they thus cannot leak if cracked. They are non-hazardous and can withstand shock and vibration better than any standard battery. As a result of increased robustness and decreased hazards, shipping costs are less than standard batteries. These batteries are considered recombinant because oxygen and hydrogen are recombined within the battery itself, resulting in virtually no water loss. Thus, these batteries do not require water to be added, further reducing maintenance actions required. (Windsun, 2011)

a. Battery Definition

The Rolls S2-3560AGM battery is selected to provide energy storage details for the HOMER simulation because of its large capacity at 3560 amp hours and robust AGM technology.

Figure 23. The Rolls S2-3560AGM battery. (From: Surrette, 2011)

The Rolls S2-3560AGM battery costs $2,327 at retail value. Even though AGM batteries do not require maintenance, HOMER's default $10 annual operations and maintenance cost per battery remain in the simulation for an overly conservative cost estimation. This way, lead acid batteries can be substituted if AGM batteries are unavailable.

The Sharp ND 224UC1 solar panel is a 36-volt system. This requires 18 two-volt batteries connected in series to match the voltage level of the solar panel system. A 36-volt bus comprised of 18 two-volt batteries make up one string. Additional strings are permitted to maximize storage potential. For the HOMER simulation, up to 12 strings are in the search space to fully exploit the trade space of all energy system combinations.

D. MADM FOR RENEWABLE ENERGY SOLUTIONS (MRES)

The multi-attribute decision-making process can aid in choosing better energy systems. The MRES process is the second phase of the approach and requires three primary inputs: stakeholder needs, an energy load profile, and renewable energy parameters (Figure 4). These inputs are discussed in Sections A, B, and C, respectively.

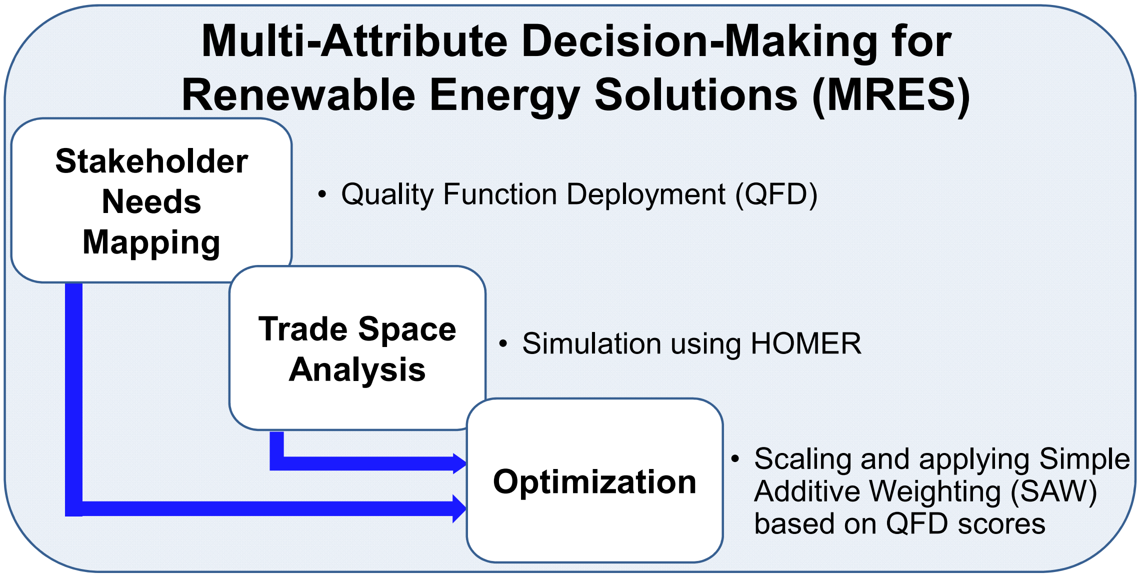

Figure 24. Multi-attribute decision-making for renewable energy solutions (MRES) process flow diagram.

The MRES process has three main functions as shown in Figure 24: stakeholder needs mapping, a trade space analysis, and optimization. These functions are discussed in Sub-sections 1, 2, and 3 respectively.

1. Stakeholder Needs Mapping

Quality function deployment is used to translate stakeholder needs into system attributes.

> Quality Function Deployment (QFD) has been practiced by leading companies around the world since 1966. Its two-fold purpose is to assure that true customer needs are properly deployed throughout the design, build and delivery of a new product, whether it be assembled, processed, serviced, or even software, and to improve the product development process itself. (Akao, 2003)

Stakeholder Needs	Weights
Security	0.61
Environment	0.05
Initial Cost	0.19
Life Cycle Cost	0.15

Table 15. Energy portfolio needs.

Table 15 shows the stakeholder needs and respective weights that must be translated into system attributes. A set of attributes are identified by selecting simulation output metrics that are associated with the needs. HOMER, the portfolio simulation tool, identifies 37 system metrics as output for each energy system configuration. Of the 37 metrics, eight are chosen as key system attributes. The top row in Table 16 provides category groupings for each of the attributes. The eight attributes are used to quantify qualitative needs with respect to security, the environment, initial and life cycle cost.

Logistics Burden	*Environment & Logistics Benefit*	*Power Sources*				*Costs*	
Total O&M Costs ($)	**Renewable Fraction (%)**	**Generator Electricity Production (kW)**	**Solar Electricity Production (kW)**	**Wind Electricity Production (kW)**	**Battery Quantity (#)**	**Initial Capital Cost ($)**	**Life Cycle Cost ($)**

Table 16. Key system attributes.

To verify that each key system attribute uniquely addresses stakeholder needs, correlations between all system attributes are examined. A correlation analysis verified redundancy does not exist among the key system attributes that were selected. The correlation analysis shown in Table 17 compares correlation coefficients among all 37 energy system metrics produced from a single HOMER simulation, in which 9,000 unique energy system designs were generated. The correlation coefficients were calculated by dividing the covariance of two attributes (for all 9,000 systems designs) by the standard deviations of the two attributes (for all 9,000 systems designs). Correlation coefficients communicate the relationship between two attributes. Highly correlated attributes will have correlation coefficients close to 1.

	PV	Wnd1	Gen	Rolls AGM 3560	Converter	Initial Capital Cost	Life Cycle Cost	Tot. Ann. Capital Cost	Tot. Ann. Repl. Cost	O&M Cost	Total Fuel Cost	Total Ann. Cost	Operating Cost	COE
PV	1.00													
W100	0.02	1.00												
Gen	-0.35	-0.08	1.00											
Rolls AGM 3560	0.09	0.01	-0.27	1.00										
Converter	0.07	0.02	-0.21	0.06	1.00									
Initial Capital Cost	0.84	0.21	-0.42	0.57	0.10	1.00								
Life Cycle Cost	-0.75	-0.18	0.30	-0.13	-0.11	-0.70	1.00							
Tot. Ann. Cap. Cost	0.84	0.21	-0.42	0.57	0.10	1.00	-0.70	1.00						
Tot. Ann. Repl. Cost	0.15	0.02	-0.09	0.55	0.03	0.40	-0.25	0.40	1.00					
O&M Cost	-0.36	0.55	0.00	0.24	-0.05	-0.06	0.58	-0.06	-0.15	1.00				
Total Fuel Cost	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00			
Total Ann. Cost	-0.75	-0.18	0.30	-0.13	-0.11	-0.70	1.00	-0.70	-0.25	0.58	0.98	1.00		
Operating Cost	-0.81	-0.20	0.34	-0.22	-0.11	-0.80	0.99	-0.80	-0.29	0.50	0.99	0.99	1.00	
COE	-0.75	-0.18	0.30	-0.13	-0.11	-0.70	1.00	-0.70	-0.25	0.58	0.98	1.00	0.99	1.00
PV Production	1.00	0.02	-0.35	0.09	0.07	0.84	-0.75	0.84	0.15	-0.36	-0.80	-0.75	-0.81	-0.75
Wind Production	0.02	1.00	-0.08	0.01	0.02	0.21	-0.18	0.21	0.02	0.55	-0.20	-0.18	-0.20	-0.18
Gen Production	-0.82	-0.19	0.35	-0.27	-0.11	-0.82	0.97	-0.82	-0.36	0.47	1.00	0.97	0.99	0.97
Tot. Electrical Production	0.95	0.19	-0.33	0.00	0.05	0.79	-0.60	0.79	0.04	-0.13	-0.66	-0.60	-0.67	-0.60
AC Primary Load Served	-0.08	0.00	0.27	-0.01	-0.06	-0.06	0.09	-0.06	-0.04	0.07	0.09	0.09	0.09	0.09
Renewable Fraction	0.84	0.20	-0.30	0.16	0.08	0.79	-0.97	0.79	0.27	-0.49	-0.98	-0.97	-0.98	-0.97
Cap. Shortage	0.08	0.00	-0.27	0.01	0.06	0.06	-0.09	0.06	0.04	-0.07	-0.09	-0.09	-0.09	-0.09
Unmet Load	0.08	0.00	-0.27	0.01	0.06	0.06	-0.09	0.06	0.04	-0.07	-0.09	-0.09	-0.09	-0.09
Excess Electricity	0.94	0.18	-0.32	-0.03	0.05	0.76	-0.55	0.76	-0.01	-0.08	-0.60	-0.55	-0.62	-0.55
Diesel	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
CO2 Emissions	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
CO Emissions	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
UHC Emissions	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
PM Emissions	-0.80	-0.20	0.34	-0.28	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
SO2 Emissions	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
NOx Emissions	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
Gen Fuel	-0.80	-0.20	0.34	-0.29	-0.11	-0.82	0.98	-0.82	-0.40	0.48	1.00	0.98	0.99	0.98
Gen Hours	-0.74	-0.23	0.31	-0.31	-0.11	-0.78	0.96	-0.78	-0.45	0.49	0.98	0.96	0.97	0.96
Gen Starts	-0.46	-0.05	0.33	-0.25	-0.34	-0.50	0.50	-0.50	-0.30	0.17	0.55	0.50	0.53	0.50
Gen Life	0.58	0.13	-0.66	0.42	0.33	0.69	-0.50	0.69	0.13	-0.02	-0.56	-0.50	-0.56	-0.50
Battery Autonomy	0.09	0.01	-0.27	1.00	0.06	0.57	-0.13	0.57	0.55	0.24	-0.29	-0.13	-0.22	-0.13
Battery Throughput	0.58	0.01	-0.25	0.40	0.06	0.66	-0.85	0.66	0.60	-0.60	-0.89	-0.85	-0.86	-0.85
Battery Life	-0.20	0.02	-0.17	0.60	0.03	0.14	0.27	0.14	-0.26	0.55	0.21	0.27	0.20	0.27
True # of Batteries	0.28	-0.06	-0.22	0.83	0.06	0.63	-0.38	0.63	0.89	-0.14	-0.54	-0.38	-0.45	-0.38

Table 17. Correlation analysis of HOMER's output metrics.

Table 17 demonstrates the correlation analysis used to distinguish between those attributes that are related with those that are unrelated. The shaded descriptions on the outside of Table 17 indicate the key system attributes that were selected. The numbers that are shaded correspond to areas where high correlation exists between attributes. For example, total fuel cost is included in the equation for life cycle cost, therefore, these two attributes are highly correlated and there is '0.98' in this cell. Therefore, it would be redundant to select both life cycle cost and total fuel cost. For another example, total fuel cost is positively correlated with generator production, as there is a '1' in this cell. Therefore, it would be redundant to select both generator production and total fuel cost, as key system attributes.

HOMER does not provide a metric to describe the total number of batteries purchased throughout the lifespan of the energy system. To account for the replacement cost associated with the purchase of additional batteries required over the lifespan of the energy system, a new metric is needed. Both metrics for battery life and number of batteries are used in the calculation of a new metric, true number of batteries, counting the total batteries required for the entire duration of the simulation.

After the needs and attributes are selected, a House of Quality (HOQ) matrix can be constructed, as shown in Table 18. Stakeholder needs are listed along with their weightings on the left, by rows. System attributes are listed on the top, by columns. The table is filled with values that reflect the relationship between the needs and the system attributes. These values either positively reward or negatively penalize the manifestation of the attribute in the energy system design. Very strong relationships are assigned a value of either positive ‘9’ (rewarding) or negative ‘9’ (penalizing). Weak relationships are assigned lower values (also positive and negative), and a zero reflects that no relationship exists.

Stakeholder Needs	Weights	Logistics Burden	Enviro & Logistics Benefit	Power Sources				Costs	
		Total O&M Costs	Renewable Fraction	Generator Production	Solar Production	Wind Production	Battery Quantity	Initial Capital Cost	Life Cycle Cost
		$	%	kW	kW	kW	#	$	$
Security (Attributes: energy independence and lives lost through logistics & sustainment convoys, i.e. fuel convoys, maintenance convoys, spares etc.)	0.61	-5	7	-9	-3	-3	-4	0	0
Environmental Impact	0.05	-3	9	-9	9	9	-3	0	0
Initial Cost	0.19	0	0	0	0	0	0	-9	0
Life Cycle Cost	0.15	0	0	0	0	0	0	0	-9

Table 18. House of Quality (HOQ) matrix.

The stakeholder needs weights and the assigned relationship values are multiplied across each row and summed by column. The absolute values of the sum are then normalized to one so that a percentage score can be assigned to each attribute.

Logistics Burden	Environment & Logistics Benefit	Power Sources				Costs	
Total O&M Costs ($)	Renewable Fraction (%)	Generator Electricity Production (kW)	Solar Electricity Production (kW)	Wind Electricity Production (kW)	Battery Quantity (#)	Initial Capital Cost ($)	Life Cycle Cost ($)
0.14	0.21	0.27	0.06	0.06	0.12	0.08	0.06

Table 19. QFD score allocated to key system attributes.

Table 19 shows the percent impact each system attribute has on influencing the system design during optimization. The total O&M cost has 14% impact, renewable factor has 21% impact, generator production has 27% impact, solar and wind production have an equal 6% impact, battery quantity has 12% impact, initial capital cost has 8% impact, and life cycle cost has 6% impact.

The reasoning behind the values assigned are described in Sub-sections a through d. The descriptions are broken into four categories: logistics burden, environmental and logistics benefit, power sources, and costs. The rationale

behind the assigned values relies on conjoint analysis (Ulrich and Eppinger, 2008). This means that subjective values are assigned to attributes based on the relationship to the need versus formal algorithms. Assigning values in this method is consistent with guidance in *Product Design and Development*, "…there are enough subtleties in this process that importance weightings can best be determined through discussion among the team members, rather than through a formal algorithm" (Ulrich and Eppinger, 2008, p. 78).

a. Logistics Burden

Under logistics burden, the total operations and maintenance cost is considered. The higher the O&M cost associated with a particular system the greater the penalty applied. Total O&M cost when attributed to security received a value of '-5'. The rationale is that if a system required weekly fuel resupply, higher rates of fuel transporting convoys would be required, which could result in higher probability of IED attacks.

Total O&M received a value of '-3' when applied to the environmental impact of a system. It is assumed that as O&M cost rises, so do the activities associated with the costs, such as convoys to move personnel that would service the energy system and the logistics to move the required maintenance parts. The required logistics has a negative impact on the environment. An example would be the carbon footprint of maintenance personnel called to troubleshoot a system.

b. Environmental and Logistics Benefit

This category refers to the renewable fraction. The renewable fraction represents the amount of renewable energy that is used throughout the lifetime of the system. When applied to security, the renewable factor is awarded a '7', because power solutions that are more renewable will have more autonomy, hence requiring less logistical support.

The renewable factor is awarded a ‘9’ for the positive impact it has on the environment. Energy systems that are renewable have little to no adverse impact on the environment when compared to fossil fuel systems.

c. Power Sources

The types of power sources considered for the next segment of the QFD include generators, photovoltaic systems, wind turbines, and battery quantity.

Generators, when applied to security, receive a value of ‘-9’. The rationale for this assessment is that generators require constant resupply, which, in turn, increases the fuel supply convoy frequency and the risk to attacks and loss of lives along supply routes. Generator-based power systems also have a negative impact on the environment. The value applied to the environment is a ‘-9’.

Solar production is given a value of ‘-3’ for security. This system would still require an expansive area that must be protected, thus adding a small security burden. As a renewable energy system, solar power systems receive the maximum value of ‘9’ for preserving the environment.

Wind production systems receive the same security value as do solar power systems. The rationale for the ‘-3’ penalty is that wind turbines require O&M support, and, thus, impose a security risk to transport personnel supporting the O&M. In the environmental context, wind production systems are renewable and, therefore, receive the maximum value of ‘9’.

Battery quantity has a ‘-4’ impact on security. Batteries are bulky and heavy and, consequently, are cumbersome to transport. The lifespan of batteries is shorter than that of wind turbines or solar arrays and, therefore, have a greater dependence on convoys for resupply, which, in turn, increases the risk to attack. Batteries have a slightly negative impact on the environment. Batteries store energy, and, thus, reduce electricity production waste. When

batteries become exhausted, they can be recycled rather than disposed of in a landfill. Batteries, however, receive a value of '-3', since batteries still affect the environment by requiring energy for transport and replacement.

d. Cost

The initial capital cost of a system is penalized with a '-9'. This penalty would encourage low initial capital cost. Likewise, the life cycle cost is given a '-9' to encourage the lowest life cycle cost. The cost penalties are unique in that they map directly to the needs of initial capital cost and life cycle cost. "In this case, the importance rating of the need becomes the importance rating of the metric" (Ulrich and Eppinger, 2008, p. 78).

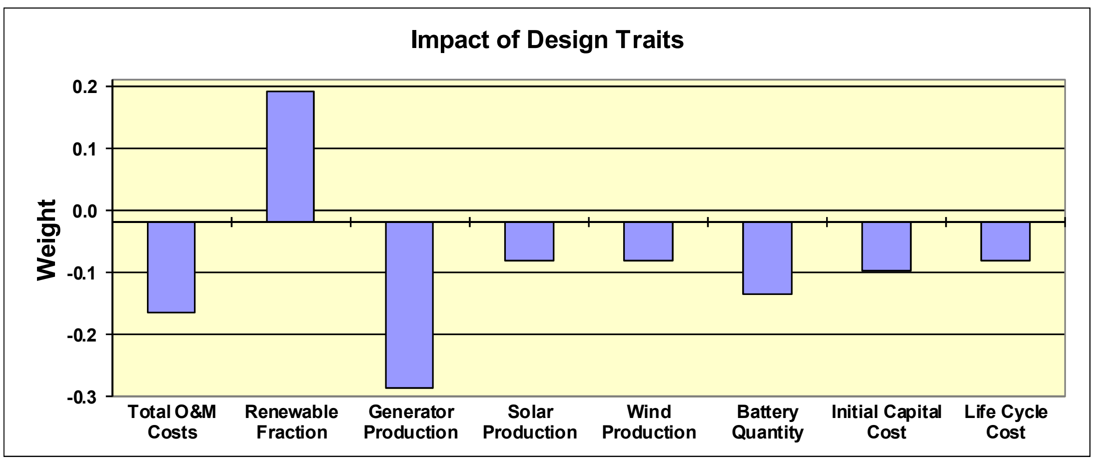

Figure 25. QFD score allocated to each system attribute.

As Figure 25 shows, generator production has the greatest impact on system design. The generator production weight is negative, indicating that the more the system's electricity production comes from diesel generator, the less desirable the system design. The next largest impact to system design is renewable fraction. The renewable fraction weight is positive, indicating that the more the system is dependent upon renewable energy sources for power production, the more desirable the system design. Total operations and maintenance cost has the third largest impact on system design. The larger the operations and maintenance cost, the less desirable the system design.

The output from the stakeholder needs mapping process consists of the eight values in Table 19 that represent the key system attributes. These values provide the required inputs to the optimization discussed in Sub-section 3.

2. Trade Space Analysis

This section describes the simulation needed to develop the trade space. Simulation software is required to build all possible combinations of systems given the load profile from Section B, the environmental inputs from Section C, and the design trade space defined in this section.

Again, HOMER is the simulation software used to evaluate all possible combinations of systems within the design trade space. The software was built specifically for modeling smaller scale renewable energy power systems for both on and off-grid applications. HOMER is a downloadable product of the National Renewable Energy Lab in Golden, Colorado. It is available free to the public at the HOMER Energy website (http://www.homerenergy.com/). The modeling software provides three main functions: simulation, optimization and sensitivity analysis. However, only HOMER's simulation function is utilized in the MRES process. The output from QFD provides weighted attribute scores that are used in lieu of HOMER's optimization function. Optimization is discussed in Sub-section 3.

HOMER provides a customizable simulation by permitting the user to define many unique resource variables and characteristics of the system. Appendix B provides detailed input data used to run the simulation for use in the MRES process. HOMER simulates an energy system by generating and comparing every combination of system components and power resources against hourly energy consumption for the life cycle of the system. The energy system life cycle duration is defined to be 25 years.

A 20-kW generator is also included in the energy portfolio. This ensures the trade space includes a way to satisfy the entire load profile using the

generator alone to reinforce any security concerns. This also permits design solutions to supplement generators at already existing facilities.

System designs that cannot satisfy the load demand for any hour during the simulation are disregarded. System designs that can satisfy the load demand are saved into a database for system optimization. The initial cost as well as costs related to the system life cycle, operations and maintenance, replacement, and fuel cost are calculated and saved in the database with each system design.

PV Array (kW)	W100 (Quantity)	Gen (kW)	S2-3560AGM (Strings)	Converter (kW)
0	0	0	0	0
10	1	20	1	15
50	2		2	20
100	3		3	25
150	4		4	
200	5		5	
250	6		6	
300	8		7	
	10		8	
	12		9	
	14		10	
	16		11	
	18		12	
	20			
	22			
	24			
	26			
	28			
	30			
	35			
	40			
	45			
	50			
	55			
	60			

Table 20. System design trade space.

The system design trade space is defined as shown in Table 20. The columns from left to right represent the photovoltaic (PV) capacity, quantity of wind turbines, size of diesel generator, number of strings of batteries, and converter size. The values in the columns indicate candidate system design sizes to meet the load demand. This trade space, when run through a HOMER simulation, results in 9,000 different combinations of systems. The trade space

must be developed so that every combination is attempted. This requires choosing various sizes of system combinations. Too many combinations lead to lengthy simulation runtimes. Using a 2.11 GHz AMD Athlon 64 X2 Dual Core Processor to simulate the full combinational set of system designs takes approximately 12 hours. Too few combinations, however, lead to a reduced solution trade space. Combinations could be reduced by creating larger increments between values; however, this, too, would reduce the solution trade space. HOMER performs optimization by selecting systems based on lowest life cycle cost. Anytime HOMER selects a system at a boundary region of the trade space, the trade space is then expanded and the simulation is repeated. This ensures the system with the lowest possible life cycle cost would be included in the database as candidate for optimization.

3. Optimization

This section describes the final function of the MRES process, optimization. The optimization function applies scaling laws to all eight system attribute values for each of the 9,000 different system combinations. Simple additive weighting (SAW) is the method to rank system scores. The design obtaining the highest score best reflects the stakeholder values and is therefore the optimal system.

The simple additive weighting method provides a quantitative way to measure how close a system design meets stakeholder needs. The first step to implement the SAW method requires scaling all key system attributes to values that lie between zero and one. The key system attributes that negatively affect the design are scaled using equation 1 in Figure 26. The only key system attribute that positively affects the design, renewable fraction, is scaled using equation 2. This scaling approach normalizes the system attributes so that values aligning with stakeholder needs are closer to one and those furthest from stakeholder needs are closer to zero. For example, life cycle cost would be scaled using equation 1. Q_j^{max} is the highest life cycle cost produced by the

simulation, and Q_j^{min} is the lowest life cycle cost produced by the simulation. $Q_{i,j}$ is the cost of the energy system for which the scaling law is being applied. The resulting value $V_{i,j}$ is a number between zero and one.

$$V_{i,j} = \begin{cases} \frac{Q_j^{max} - Q_{i,j}}{Q_j^{max} - Q_j^{min}} & \text{if } Q_j^{max} - Q_j^{min} \neq 0 \\ 1 & \text{if } Q_j^{max} - Q_j^{min} = 0, \end{cases} \quad (1)$$

$$V_{i,j} = \begin{cases} \frac{Q_{i,j} - Q_j^{min}}{Q_j^{max} - Q_j^{min}} & \text{if } Q_j^{max} - Q_j^{min} \neq 0 \\ 1 & \text{if } Q_j^{max} - Q_j^{min} = 0. \end{cases} \quad (2)$$

Figure 26. Scaling formula. (From: Zeng et al., 2004)

Table 21 lists the top seven of 9,000 scaled results from one simulation. HOMER arranges the database to display systems in ascending order for life cycle cost (circled), since HOMER's inherent optimization function optimizes based on life cycle cost only. Highlighted in the first row is the system HOMER selects as optimal.

	0.062	0.062	0.267	0.116	0.077	0.060	0.144	0.212	<-- QFD Scores	
	PV Production	Wind Production	Gen Production	True # of Batteries	Total Capital Cost	Life Cycle Cost	Total O&M Cost	Ren. Fraction		
#	kWh/yr	kWh/yr	kWh/yr	#	$	$	$/yr	%		SAW Score
1	0.499998211	0.416657577	1	0.312714777	0.437590383	1	0.543443354	1		0.744332899
2	0.499998211	0.333322945	1	0.329501916	0.45496921	0.998852642	0.526494202	1		0.739995307
3	0.499998211	0.416657577	1	0.312714777	0.434782365	0.998691771	0.543443354	1		0.744036998
4	0.499998211	0.333322945	1	0.333333333	0.425565044	0.997608597	0.494380018	1		0.733479912
5	0.499998211	0.333322945	1	0.329501916	0.452161191	0.997544412	0.526494202	1		0.739699406
6	0.499998211	0.333322945	1	0.333333333	0.41292896	0.997157871	0.494380018	1		0.73247713
7	0.499998211	0.333322945	1	0.333333333	0.422757025	0.996300368	0.494380018	1		0.733184012

Table 21. HOMER optimization results sorted on lowest life cycle cost.

After the scaling laws are applied to all 9,000 system combinations, a SAW score is assigned to each combination. The SAW score is generated by first multiplying the QFD scores for each key system attribute by the scaled system attribute. Then, the products are summed by row producing a SAW score that lies between zero and one.

The systems are then sorted based on their scores in descending order. The highest scoring system is the optimized combination of energy solutions.

Since the stakeholder needs are mapped through to the final weighting and ranking, the SAW method yields systems that best meet the needs of the stakeholders. The basis for this claim is the assumptions used in creating the impact weights in the HOQ matrix, and the AHP weights for the stakeholder needs. Table 22 shows a new prioritization of energy systems based on their SAW scores (circled) from the largest to the smallest rather than on the life cycle cost alone. The energy system that is highlighted at the top of the list has the optimal combination of energy production solutions because it best satisfies stakeholder needs.

	0.062	0.062	0.267	0.116	0.077	0.060	0.144	0.212	<-- QFD Scores	
	PV Production	Wind Production	Gen Production	True # of Batteries	Total Capital Cost	Life Cycle Cost	Total O&M Cost	Ren. Fraction		
#	kWh/yr	kWh/yr	kWh/yr	#	$	$	$/yr	%		SAW Score
2727	0.499998211	0.983326841	0.907032614	0.137931034	0.653747441	0.924238794	0.991436218	0.94		0.797804979
2781	0.499998211	0.983326841	0.907032614	0.137931034	0.650939423	0.922930565	0.991436218	0.94		0.797509079
2188	0.499998211	0.983326841	0.922545155	0.122807018	0.624343275	0.933955465	0.968421053	0.95		0.797318039
2834	0.499998211	1	0.904443921	0.137931034	0.656152509	0.921519312	1	0.93		0.797269668
2259	0.499998211	0.983326841	0.922545155	0.122807018	0.621535256	0.932647235	0.968421053	0.95		0.797022139
2887	0.499998211	1	0.904443921	0.137931034	0.653344491	0.920211083	1	0.93		0.796973768
2348	0.499998211	1	0.920329078	0.099099099	0.626748343	0.931201846	0.976984835	0.95		0.7962436

Table 22. Optimization results sorted on SAW score.

The optimal system selected has slightly higher life cycle cost than does the energy system selected by HOMER, but it has lower capital cost and significantly lower operations and maintenance cost. It represents the optimal system corresponding to the weighted needs and the weights of the individual stakeholders.

E. OPTIMAL ENERGY RUBRIC GENERATION

The last phase of the approach (see Figure 4) is the generation of an optimal energy rubric. The rubric provides the functionality of a look-up table to select the optimal energy system based on stakeholder needs for given environmental parameters. The rubric is a matrix that contains all optimal energy system portfolios for all possible combinations of solar and wind for a given region. In the application of this approach to Afghanistan, four solar irradiance bands and seven wind classes are generated, resulting in 28 solar and wind combinations, and thus, a unique optimal energy system design exists for each

of these combinations. Therefore, a four-by-seven matrix is needed to display all 28 combinations.

The process conducted in Section C breaks down all solar and wind data for Afghanistan into solar irradiance bands and wind classes. The four solar irradiance bands, captured in Table 8, make up the row headings in the first column on the left side of the matrix. The seven wind classes captured in Table 10 make up the column headings in the first row along the top of the matrix. The matrix is then populated by iteratively conducting the last two MRES functions (trade space analysis and optimization) for every combination of solar and wind in the matrix. This requires conducting 28 custom simulations and optimizations. The results in Table 23 provide a look-up table for a civil engineer to quickly determine the optimal energy system portfolio for all solar and wind conditions within the region, and, thus, for any location within that region.

		Poor	Marginal	Fair	Good	Excellent	Outstanding	Superb	Scale
FBCF = $4.82/liter		1	2	3	4	5	6	7	Wind Class
Load Profile: ExFOB		0 - 200 (4.28)	200 - 300 (5.97)	300 - 400 (6.73)	400 - 500 (7.48)	500 - 600 (7.55)	600 - 800 (7.85)	> 800 (8.59)	W/m2 at 50m m/sec
s1	4.0 - 4.5 (4.25)	1270 200kW PV 54 Batteries 1 Wind Turbine	2172 200kW PV 54 Batteries 2 Wind Turbines	2185 200kW PV 54 Batteries 5 Wind Turbines	1011 200kW PV 54 Batteries 14 Wind Turbines	1188 150kW PV 54 Batteries 16 Wind Turbines	861 150kW PV 54 Batteries 18 Wind Turbines	615 150kW PV 54 Batteries 18 Wind Turbines	
s2	4.5 - 5.0 (4.75)	1342 200kW PV 54 Batteries	2465 200kW PV 54 Batteries	1878 150kW PV 54 Batteries 10 Wind Turbines	975 150kW PV 54 Batteries 14 Wind Turbines	972 150kW PV 54 Batteries 14 Wind Turbines	1155 150kW PV 54 Batteries 12 Wind Turbines	605 150kW PV 54 Batteries 16 Wind Turbines	
s3	5.0 - 5.5 (5.25)	1571 150kW PV 54 Batteries 1 Wind Turbines	2727 150kW PV 54 Batteries 1 Wind Turbines	1743 150kW PV 54 Batteries 8 Wind Turbines	1398 150kW PV 54 Batteries 10 Wind Turbines	1803 150kW PV 54 Batteries 8 Wind Turbines	1174 150kW PV 54 Batteries 12 Wind Turbines	642 150kW PV 54 Batteries 16 Wind Turbines	
s4	5.5 - 6.0 (5.75)	530 150kW PV 90 Batteries	2203 150 kW PV 54 Batteries 2 Wind Turbines	1874 150 kW PV 54 Batteries 6 Wind Turbines	1430 150 kW PV 54 Batteries 10 Wind Turbines	1742 150 kW PV 54 Batteries 8 Wind Turbines	635 100 kW PV 54 Batteries 20 Wind Turbines	747 100 kW PV 54 Batteries 16 Wind Turbines	
	kWh/m^2/day								

Table 23. Optimal energy rubric for energy portfolio decision-making.

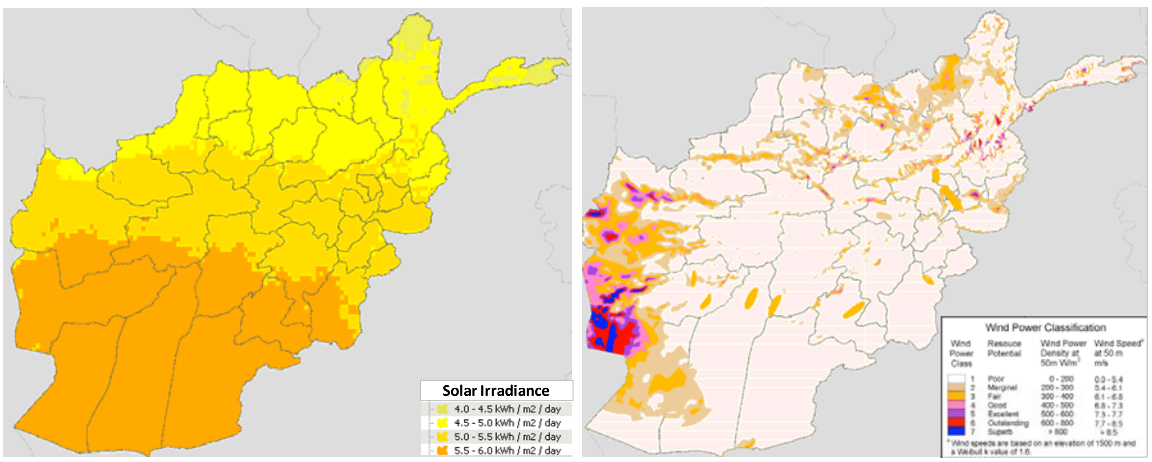

Figure 27. Solar irradiance and wind energy potential maps. (From: NREL, 2011)

The four-by-seven matrix in Table 23 captures all possible solar and wind combinations corresponding to any location throughout the entire country of Afghanistan. The column and row headers are color coded to facilitate quick matching from the environmental maps in Figure 27. The matching colors inside the Table 23 signify energy systems that are identical. Thus, 19 unique system designs are required to satisfy all 28 possible locations. The cells in Table 23 contain a subset of the data taken from the output of HOMER simulations, after optimal system are identified through optimization. Appendix A contains all characteristics for optimal energy system designs identified in each of the 28

optimizations. The information contained in the rubric provides the system ID, the quantity of photovoltaic cells, the number of batteries, and the number of wind turbines required. The system ID is used to look up supplementary system characteristics, which include all cost and emissions data also provided in Appendix A. All systems in this rubric require a 20-kW generator. Augmenting generators with renewables minimizes the required generator usage, commensurate with QFD scores for key system attributes (Figure 25).

The optimal energy rubric provides a method USACE civil engineers can use to quickly determine the optimal energy system for any given location in Afghanistan, without running a model or requiring simulation software. To illustrate its use, for example, a USACE civil engineer would first gather environmental data, provided in Figure 27, for the location where power is needed. The environmental data would then be used to look-up, in Table 23, the optimal energy system characteristics for that specific location.

IV. DISCUSSION OF RESULTS

Section A describes trending that occurs within the optimal energy rubric. Section B provides a sensitivity analysis with respect to a changing fully burdened cost of fuel.

A. OPTIMAL ENERGY RUBRIC TRENDS

The optimal energy rubric exhibits expected overall trends in addition to unexpected anomalies. As available wind potential increases, the number of wind turbines required increases. However, unexpected anomalies occur, as displayed in sola irradiance rows s3 and s4, in the wind class column 5, in Table 23. For these environmental conditions, the number of wind turbines decrease as wind speed increases, and, therefore, do not follow a linear trend. Another remarkable trend is that the more solar irradiance and wind potential are available, the less photovoltaic capacity is required. In this section, the results within the optimum energy rubric are analyzed so that conclusions can be drawn about which environmental condition has a greater influence in design and which attributes drive cost.

To assess which environmental condition has greater influence in design, plots were generated to first determine if environmental conditions have interdependencies that influence the optimal design. Figures 28 and 29 were generated using JMP data visualization software (JMP, 2010). These figures were generated by plotting the number of wind turbines (Figure 28) and photovoltaic capacity (Figure 29) against all wind classes and solar irradiance bands, for each of the 28 energy systems in the optimal energy rubric.

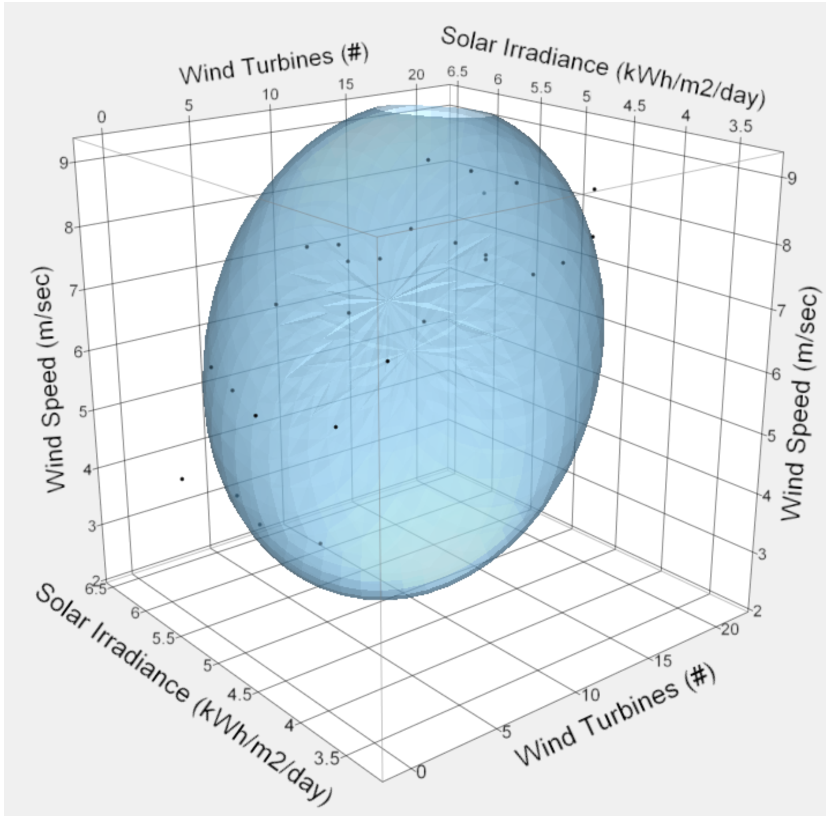

Figure 28. All 28 data points in the optimal energy rubric for wind turbines vs wind speed vs solar irradiance.

Figure 28 illustrates that wind speed influences the number of wind turbines; as wind speed increases, the number of wind turbines increase. This graph also indicates that varying solar irradiance levels do not affect the number of wind turbines in the system, as the data points are uniformly distributed. The ellipse is a function of the means, standard deviations, and correlations of the data in the plot (JMP, 2010). The ellipse covers at least 50% of the data points and aids in visualizing the trends in the data. It also indicates a region for which there is a high probability that other possible solutions might exist, assuming a multivariate normal distribution.

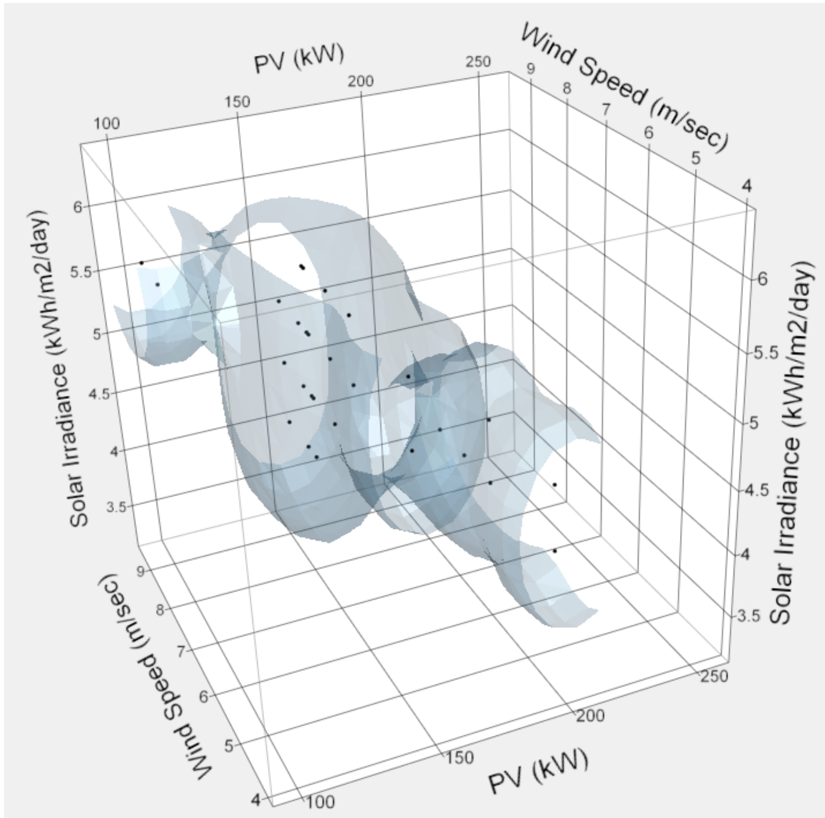

Figure 29. All 28 data points in the optimal energy rubric for photovoltaic (PV) capacity vs solar irradiance vs wind speed.

Figure 29 illustrates that changes in wind speed generally do not influence the required amount of photovoltaic (PV) capacity. To aid in cluster discrimination, a shaded contour is applied to the data. A probabilistic distribution is not used because the data is clustered into regions of photovoltaic capacity, and, thus, a nonparametric contour is applied and includes 90% of the data points. From this figure, it is observed that only at very high wind speeds is photovoltaic capacity influenced. With wind classes 7 and 8, optimal systems have less photovoltaic capacity, as indicated by the two 100 kW data points in the upper left quadrant of Figure 29.

Figures 28 and 29 demonstrated that environmental conditions generally do not have interdependencies that influence system design. Next, a correlation analysis is performed to assess which environmental condition has greater

influence in design. The correlation analysis communicates trends within the optimal energy rubric. Figure 30, also generated by JMP data visualization software, shows the relationships between the key system attributes and environmental conditions for all 28 energy system designs captured in the optimal energy rubric.

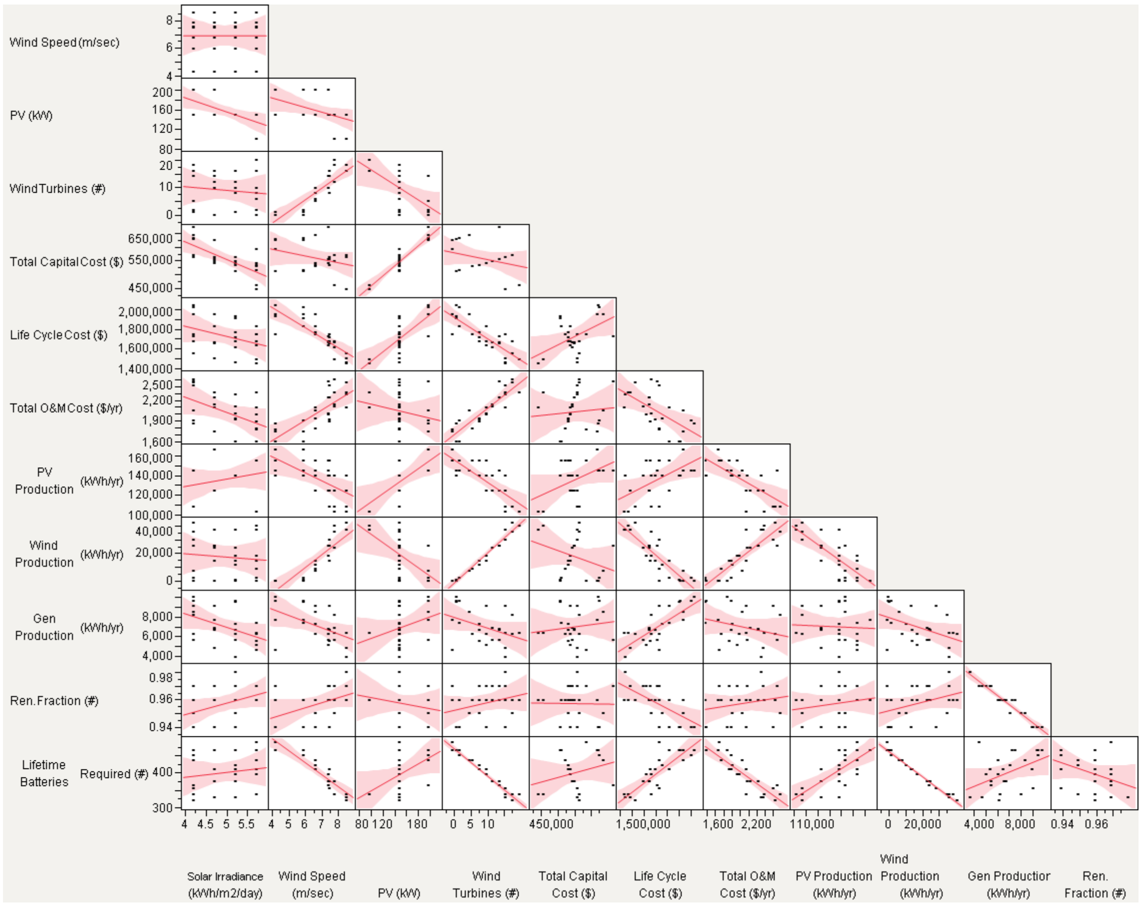

Figure 30. Correlation table of all 28 energy systems, key system attributes, and environmental conditions.

In Figure 30, linear trend lines are included as best-fit to the data. The slope of the line indicates attributes correlating either positively or negatively. Correlations with data points closer to the trend lines have higher R-square values, and thus, indicate stronger relationships. The shaded regions have lower R-square values, and thus, indicate that a linear fit can vary considerably. For example, the data in the solar irradiance column does not fit a linear trend with

any attribute besides total capital cost. The wind speed column, however, contains data that more closely correlates to system attributes. Therefore, the correlation analysis indicates that wind speed has greater sensitivity in influencing in system design, more so than solar irradiance.

The trend lines in Figure 30 also convey information about which attributes drive cost. For example, life cycle cost positively correlates with generator production, thus, life cycle cost is greater for those energy systems that depend more on the diesel generator for energy production. Also, life cycle cost negatively correlates with the number of wind turbines. Therefore, with respect to the optimal energy rubric, energy systems with more wind turbines have a lower life cycle cost than energy systems with less wind turbines.

Of the 28 possible environmental combinations, 19 unique energy system designs are required to address all possible locations. All energy systems contain a 20-kW generator and a battery bank configuration of either 54 or 90 batteries. All designs require some combination of PV capacity and wind production in the ranges of 100 kW to 200 kW of PV capacity and 0 to 20 total wind turbines. Generally, the more solar irradiance available, the less PV capacity required. Conversely, the greater the wind speed, the greater the number of wind turbines required. The greater the number of wind turbines the energy system has, the lower the life cycle cost. Wind speed also has a greater sensitivity in influencing system design and life cycle cost, than does solar irradiance. This understanding can aid developmental planners in choosing suitable locations to build infrastructure by using the wind speed maps in Figure 27. However, regardless of wind speed available, there is not a location in Afghanistan where renewable energy is omitted from the optimal energy rubric.

B. SENSITIVITY ANALYSIS—FULLY BURDENED COST OF FUEL

This section describes a sensitivity analysis of the approach for renewable energy portfolio selection, to determine how changes in the fully burdened cost of fuel affect the resulting energy system selection. The analysis involves varying

the FBCF but keeping the renewable energy parameters and the energy load profile fixed for a given location in Afghanistan.

Section A in Chapter I addresses the importance of considering the FBCF versus simply considering the cost per gallon charged for the fuel price alone. There are no official records of the FBCF for Afghanistan. In 2008, a National Defense Industrial Association (NDIA) study concluded the FBCF for an immature theater was $17.44 per gallon. Afghanistan is indicative of an immature theater, and $17.44 in 2008 dollars is $18.25 in 2011 dollars, which equates to $4.82 per liter. The $4.82-per-liter cost is used to represent the FBCF in the analysis (Tables 23 and 24).

To perform a sensitivity analysis with respect to the FBCF, three additional FBCF values are examined while keeping the solar and wind resources fixed. The analysis used three additional FBCF prices with the environmental conditions circled in Table 24. For this location, the average annual solar irradiance is 5.25 kWh/m^2/day and the annual average wind speed is 5.97 m/sec. These particular environmental conditions are selected because they characterize most of Afghanistan, including the nation's capital, Kabul.

		Poor	Marginal	Fair	Good	Excellent	Outstanding	Superb	Scale
FBCF = $4.82/liter		1	2	3	4	5	6	7	Wind Class
Load Profile: ExFOB		0 - 200 (4.28)	200 - 300 (5.97)	300 - 400 (6.73)	400 - 500 (7.48)	500 - 600 (7.55)	600 - 800 (7.85)	> 800 (8.59)	W/m2 at 50m m/sec
s1	4.0 - 4.5 (4.25)	1270 200kW PV 54 Batteries 1 Wind Turbine	2172 200kW PV 54 Batteries 2 Wind Turbines	2185 200kW PV 54 Batteries 5 Wind Turbines	1011 200kW PV 54 Batteries 14 Wind Turbines	1188 150kW PV 54 Batteries 16 Wind Turbines	861 150kW PV 54 Batteries 18 Wind Turbines	615 150kW PV 54 Batteries 18 Wind Turbines	
s2	4.5 - 5.0 (4.75)	1342 200kW PV 54 Batteries	2465 200kW PV 54 Batteries	1878 150kW PV 54 Batteries 10 Wind Turbines	975 150kW PV 54 Batteries 14 Wind Turbines	972 150kW PV 54 Batteries 14 Wind Turbines	1155 150kW PV 54 Batteries 12 Wind Turbines	605 150kW PV 54 Batteries 16 Wind Turbines	
s3	5.0 - 5.5 (5.25)	1571 150kW PV 54 Batteries 1 Wind Turbines	2727 150kW PV 54 Batteries 1 Wind Turbines	1743 150kW PV 54 Batteries 8 Wind Turbines	1398 150kW PV 54 Batteries 10 Wind Turbines	1803 150kW PV 54 Batteries 8 Wind Turbines	1174 150kW PV 54 Batteries 12 Wind Turbines	642 150kW PV 54 Batteries 16 Wind Turbines	
s4	5.5 - 6.0 (5.75)	530 150kW PV 90 Batteries	2203 150 kW PV 54 Batteries 2 Wind Turbines	1874 150 kW PV 54 Batteries 6 Wind Turbines	1430 150 kW PV 54 Batteries 10 Wind Turbines	1742 150 kW PV 54 Batteries 8 Wind Turbines	635 100 kW PV 54 Batteries 20 Wind Turbines	747 100 kW PV 54 Batteries 16 Wind Turbines	
	kWh/m^2/day								

Table 24. Reference for location of three additional FBCF prices.

To cover a wide spectrum of FBCF prices, two additional low values and one additional high value are selected. To represent a very low FBCF, $3.50 per

gallon ($0.92 per liter) is selected. This value is chosen because it represents the average price per gallon in the U.S.

Based on the U.S. Army's Research, Development, and Engineering Command (RDECOM) study, $7.50 per gallon ($1.98 per liter) represents a 400-mile round-trip convoy from Bagram, Afghanistan, where air support is provided for up to 20% of the total mileage (Blankenship and Cole, 2009).

Finally, a value of $30 per gallon ($7.92 per liter is selected to represent a random FBCF. The four FBCF values are displayed in Table 25.

$ / Gallon	$ / Liter	
$3.50	$0.92	Slightly less than U.S. average
$7.50	$1.98	RDECOM's FBCF value
$18.25	$4.82	NDIA FBCF workshop
$30.00	$7.92	Large FBCF

Table 25. Four FBCF values analyzed.

The trade space analysis now incorporates the three additional FBCF values. The simulation and optimization is conducted again using the new data. Table 26 provides four unique energy system designs corresponding to the changing FBCF values.

		Marginal	Marginal	Marginal	Marginal	Scale
		2	2	2	2	Wind Class
Load Profile: ExFOB		200 - 300 (5.97)	200 - 300 (5.97)	200 - 300 (5.97)	200 - 300 (5.97)	W/m2 at 50m m/sec
		$3.50	$7.50	$18.25	$30.00	FBCF $ / Gallons
s3	5.0 - 5.5 (5.25)	2794 200kW PV 162 Batteries 4 Wind Turbines No Generator	256 200kW PV 162 Batteries 4 Wind Turbines No Generator	2727 150kW PV 54 Batteries 1 Wind Turbines	3641 150kW PV 54 Batteries 0 Wind Turbines	
	$kWh/m^2/day$					

Table 26. Optimized energy system designs with respect to four FBCF values.

As shown by Table 26, as the FBCF increases, the number of wind turbines and PV capacity decrease. Furthermore, when FBCF is $3.50 and $7.50 per gallon, the optimized energy system does not even contain a generator, the system is entirely renewable.

To better understand what is happening to the rather counter intuitive results in Table 26, Figure 31 shows the correlation between the FBCF, the SAW score, and all eight key system attributes. The legend, located to the right of center, indicates the color codes that correspond to the four FBCF data points.

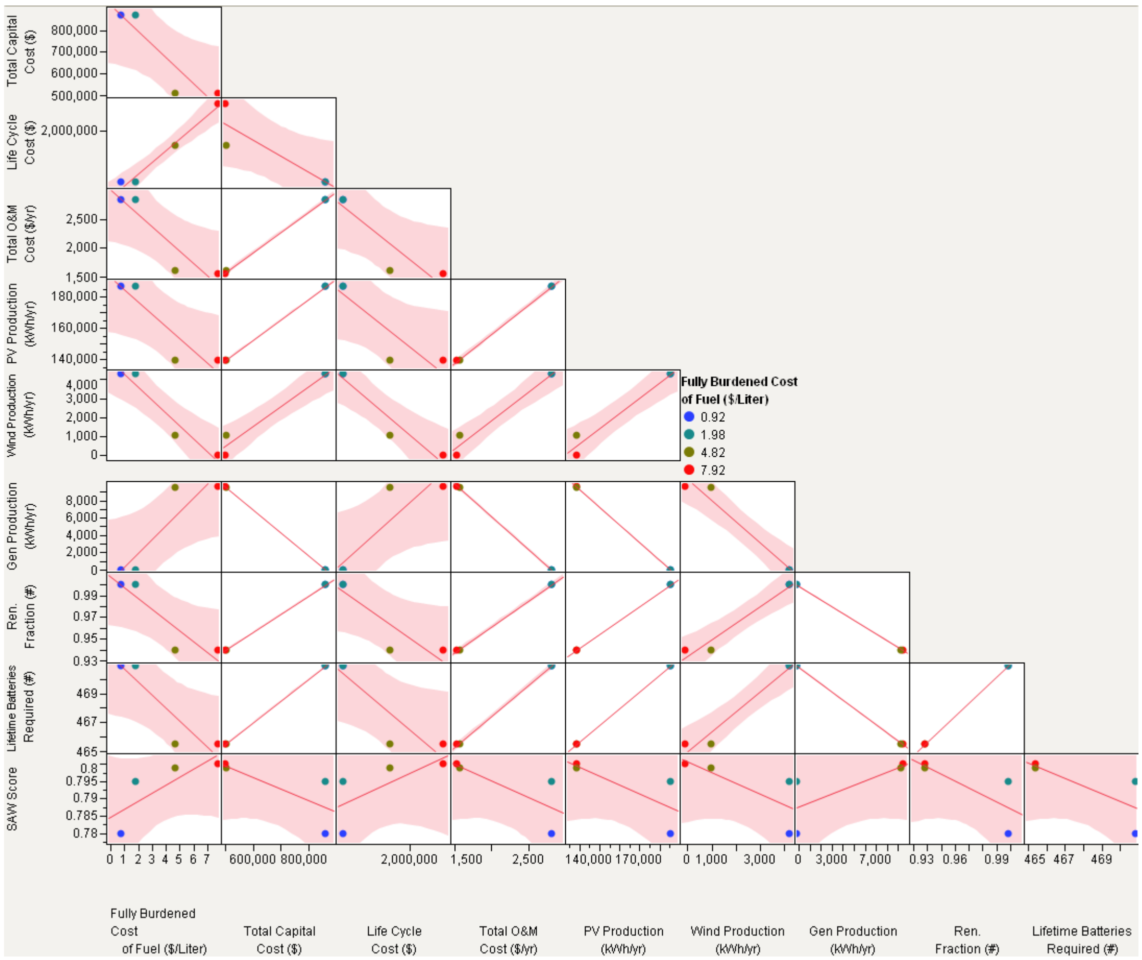

Figure 31. Four FBCF runs.

The correlation matrix shown in Figure 31 supports the following conclusions. Fuel cost and life cycle cost are positively correlated at 0.98 as shown in Table 17. Therefore, as FBCF increases, life cycle cost increases. Even though greater wind production decreases life cycle cost, as shown in Figure 31, life cycle cost has only 6% impact on the final design solution as shown in Table 19.

Greater wind production results in higher operations and maintenance cost as shown in both Figure 30 and 31. This could be another explanation for reduced wind generation when FBCF increases. Wind turbines are positively correlated with O&M cost at 0.55 as shown in Table 17. O&M cost is the third highest stakeholder need and yields 14% impact on the final design solution, 8% higher than life cycle cost. Therefore, the optimization process seeks to reduce O&M cost more so than life cycle cost.

Even though the trend in Table 26 demonstrates that MRES reduces wind generation as FBCF increases, and even with increasing fuel costs, the larger FBCF value, however, is expected to decrease over time. As a country develops, its infrastructure and security improve, thus, decreasing the FBCF (Blankenship and Cole, 2009).

The results of this sensitivity analysis indicate that, for a wide range of FBCFs, renewable power production should supplement or replace diesel generator systems. This analysis shows that the optimization is consistent with stakeholder preferences for increased security, reduced environmental impact, and minimal initial and life cycle cost.

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V. CONCLUSION

The significance of this new approach to regional energy system portfolio decision-making (see Figure 4), is that its output, an optimal energy rubric (Table 23), provides a tool that quickly communicates to decision-makers in Afghanistan exactly what mix of renewable and non-renewable energy systems need to be constructed for any given location within the country. By utilizing Brassard's full analytical criteria method for prioritization (Brassard, 1989), quality function deployment, simulation, and optimization techniques, this approach balances competing stakeholder needs to facilitate easy energy portfolio decision-making by providing an optimal energy rubric.

Energy plays a vital role in several areas affecting the success of Afghanistan in achieving its objective of being a secure and sovereign nation capable of sustaining its own defense and economy (Afghanistan National Development Strategy, 2008). ANSF currently rely heavily on diesel fueled generators to power the vast majority of the police and defense energy needs. Over-reliance on fossil fuel energy systems poses problems such as logistical burdens, security risks, environmental concerns, and increased life cycle costs. Sustainable alternative energy solutions, such as combinations of renewable with non-renewable energy systems, need to be developed.

The approach developed in this research aids implementing such energy solutions. This three-phased approach determines an optimal energy portfolio through specific input generation, application of a MRES process, and the generation of an optimal energy rubric. Ender provides the foundation for the approach, namely, the use of MADM for energy portfolio decision-making (Ender et al., 2010), which is modified in phase two of the approach. Solar irradiance, wind potential, and current infrastructure development in Afghanistan provide an ideal environment for demonstrating the application of the approach. In addition, the Marine Corps' ExFOB offers the model energy load profile for relatively small-scale ANSF energy system applications.

The approach determines the optimal energy system by selecting the energy system that best meet the needs of all stakeholders. For example, when solar irradiation averages 5.25 kWh/m^2/day and wind potential averages between 200–300 W/m^2 (at 50m), the optimal energy system combination includes: one 20-kW diesel generator, 150-kW PV cells, one wind turbine, and 54 cell battery bank. This system would generate 139,780 kWh/year of solar energy, 1,070 kWh/year of wind energy, and minimal diesel generator production of 9,481 kWh/year. The life cycle cost of this system for a 25-year lifespan is 2.5 times less expensive than that of a diesel generator only system, thus minimizing life cycle cost. The operations and maintenance cost of the optimal energy system is roughly one-third the cost of the diesel generator only system, therefore, the optimal energy system reduces the logistics burden, and, thus, reduces security risks involved in O&M logistics. The optimal energy system uses just 8% of the fuel used for the diesel generator only system. Therefore, the optimal energy system significantly reduces fuel logistics, thus, increases security. The diesel generator only system does not use any renewable energy, while 94% of the energy produced by the optimal energy system is renewable, and therefore, addresses the need for reduced environmental impact.

The initial cost for an optimized energy system located in Kabul is $511,234 compared to a diesel generator only system at $18,000. However, the 25-year life cycle cost of the renewable system is $1,911,481, while the diesel generator only system is $5,093,536. The USACE still have plans to construct an additional 600 facilities for the ANP alone (USACE, 2011). If this approach were applied to the remaining USACE construction projects in Afghanistan, $1.8 billion dollars could be saved over the next 25 years.

The results captured in the optimal energy rubric indicate that optimal energy solutions gravitate towards systems utilizing minimal amounts of diesel generator electricity production. Less dependence on diesel generator electricity production is observed as solar irradiance and average wind speed increase. Not all trends within the rubric are linear as solutions depend upon a variety of

system attributes which are interrelated. Also, as more solar irradiance and wind potential are available, less photovoltaic capacity is required. However, wind speed has greater sensitivity in influencing in the system design and life cycle cost, than does solar irradiance. Developmental planners can utilize this information to build infrastructure in areas with higher average annual wind speeds.

As shown by the sensitivity analysis, which involves varying the FBCF for a given location in Afghanistan but keeping the renewable energy parameters fixed, as FBCF increases, systems with less wind turbines are selected. Wind turbine generation thus positively correlates with O&M cost. Therefore, the optimization chooses to minimize these costs when introduced with a higher FBCF burden. Even for a wide range of FBCFs, renewable power production should still supplement or replace diesel generator systems. This analysis indicates the approach is consistent with stakeholder preferences for increased security, reduced environmental impact, and minimal initial and life cycle cost.

Thus, the research question is effectively addressed by demonstrating that this approach to optimizing renewable energy systems can indeed aid in choosing better energy systems for Afghanistan. There is not a location in Afghanistan where renewable energy is omitted from the optimal energy rubric. In addition, this approach is applicable not only to Afghanistan, but also any region on the globe.

A. FURTHER DEVELOPMENT

Areas for further exploration follow.

- Use methods other than AHP, such as Swing Weights, to assign weights to needs, as they may offer alternative weights for needs that would ultimately change the optimized system selection. A sensitivity analysis could also be performed on these weights.

- Break security need into separate needs. This may permit system optimization to tailor the specific design to more detailed needs.
- Choose larger wattage wind turbines. This would reduce the number of wind turbines required when higher wind classes are available, offering even greater optimized system design.
- Remove the $859 cost for wind towers. Rooftop application permits heights of at least 10 meters, and, thus, would not require the additional cost of standalone towers.
- Introduce several wind turbines with unique and complementary power curves. This would allow multiple wind turbine varieties within a single system, better matching the wind resource profile available for a given location.
- Perform FBCF runs for the entire four-by-seven matrix. This would demonstrate consistency of the matrix given fuel cost variability. It would also offer a third dimension to the optimal energy rubric to permit adaptation to a changing FBCF.
- Introduce replacement cost to both solar and wind, thereby better balancing solar and wind cost data. This can be accomplished by increasing the simulation timeline beyond 25 years. This injects replacement cost for solar panels since solar panels have a 25-year life span.
- Remove O&M cost for AGM batteries (currently set at $10/yr/battery). This would represent an AGM battery only solution versus a flexible battery solution. The benefit would be lower O&M cost and could perhaps lead to other design solutions.
- Conduct a design of experiments to more finely tune and reduce the search space. Rather than conducting a full factorial that can take up to 12 hours to run, this would reduce simulation run time.

Appendix A—Output Data

Fully Burdened Cost of Fuel ($/Liter)	Solar Irradiance (kWh/m2/day)	Wind Speed (m/sec)	Wind Matrix Coordinate (w)	Solar Matrix Coordinate (s)	System ID (#)	PV (kW)	Wind Turbines (#)	Generator (kW)	Batteries (#)	Converter (kW)	Total Capital Cost ($)	Life Cycle Cost ($)	Tot. Ann. Cap. Cost ($/yr)	Tot. Ann. Repl. Cost ($/yr)	Total O&M Cost ($/yr)	Total Fuel Cost ($/yr)	Total Ann. Cost ($/yr)	Operating Cost ($/yr)	COE ($/kWh)	PV Production (kWh/yr)
4.82	4.25	8.59	7	1	615	150	18	20	54	20	569,476	1,547,221	22,779	26,526	2,449	10,135	61,889	39,110	0.61	108,396
4.82	4.25	7.85	6	1	861	150	18	20	54	20	569,476	1,676,284	22,779	28,533	2,501	13,239	67,051	44,272	0.661	108,396
4.82	4.25	7.55	5	1	1188	150	16	20	54	20	562,624	1,748,163	22,505	30,195	2,417	14,810	69,927	47,422	0.689	108,396
4.82	4.25	7.48	4	1	1011	200	14	20	54	20	671,822	1,728,497	26,873	30,633	2,467	9,167	69,140	42,267	0.681	144,528
4.82	4.25	6.73	3	1	2185	200	5	20	54	20	640,988	1,946,716	25,640	36,384	2,047	13,799	77,869	52,229	0.767	144,528
4.82	4.25	5.97	2	1	2172	200	2	20	54	20	630,710	2,018,556	25,228	38,046	1,910	15,558	80,742	55,514	0.796	144,528
4.82	4.25	4.28	1	1	1270	200	1	20	54	20	627,284	2,041,921	25,091	38,530	1,867	16,189	81,677	56,585	0.805	144,528
4.82	4.75	8.59	7	2	605	150	16	20	54	20	562,624	1,500,721	22,505	27,328	2,304	7,892	60,029	37,524	0.592	124,201
4.82	4.75	7.85	6	2	1155	150	12	20	54	20	548,920	1,663,323	21,957	31,255	2,137	11,185	66,533	44,576	0.656	124,201
4.82	4.75	7.55	5	2	972	150	14	20	54	20	555,772	1,657,266	22,231	30,961	2,241	10,858	66,291	44,060	0.653	124,201
4.82	4.75	7.48	4	2	975	150	14	20	54	20	555,772	1,664,162	22,231	31,107	2,243	10,986	66,566	44,336	0.656	124,201
4.82	4.75	6.73	3	2	1878	150	10	20	54	20	542,068	1,828,910	21,683	34,665	2,088	14,720	73,156	51,474	0.721	124,201
4.82	4.75	5.97	2	2	2465	200	0	20	54	20	623,858	1,947,890	24,954	38,750	1,752	12,460	77,916	52,961	0.768	165,601
4.82	4.75	4.28	1	2	1342	200	0	20	54	20	623,858	1,947,890	24,954	38,750	1,752	12,460	77,916	52,961	0.768	165,601
4.82	5.25	8.59	7	3	642	150	16	20	54	20	562,624	1,458,888	22,505	27,233	2,278	6,340	58,356	35,851	0.575	139,780
4.82	5.25	7.85	6	3	1174	150	12	20	54	20	548,920	1,614,417	21,957	31,295	2,108	9,217	64,577	42,620	0.636	139,780
4.82	5.25	7.55	5	3	1803	150	8	20	54	20	535,216	1,712,158	21,409	34,392	1,912	10,774	68,486	47,078	0.675	139,780
4.82	5.25	7.48	4	3	1398	150	10	20	54	20	542,068	1,677,788	21,683	33,248	2,012	10,169	67,112	45,429	0.661	139,780
4.82	5.25	6.73	3	3	1743	150	8	20	54	20	535,216	1,768,544	21,409	35,664	1,928	11,741	70,742	49,333	0.697	139,780
4.82	5.25	5.97	2	3	2727	150	1	20	54	20	511,234	1,911,481	20,449	38,995	1,604	15,411	76,459	56,010	0.754	139,780
4.82	5.25	4.28	1	3	1571	150	1	20	54	20	511,234	1,923,168	20,449	39,245	1,607	15,625	76,927	56,477	0.758	139,780
4.82	5.75	8.59	7	4	747	100	16	20	54	20	446,574	1,452,456	17,863	27,910	2,091	10,234	58,098	40,235	0.573	103,343
4.82	5.75	7.85	6	4	635	100	20	20	54	20	460,278	1,488,295	18,411	28,516	2,312	10,293	59,532	41,121	0.587	103,343
4.82	5.75	7.55	5	4	1742	150	8	20	54	20	535,216	1,670,181	21,409	34,421	1,887	9,090	66,807	45,399	0.658	155,014
4.82	5.75	7.48	4	4	1430	150	10	20	54	20	542,068	1,636,795	21,683	33,288	1,988	8,513	65,472	43,789	0.645	155,014
4.82	5.75	6.73	3	4	1874	150	6	20	54	20	528,364	1,741,867	21,135	36,623	1,792	10,125	69,675	48,540	0.687	155,014
4.82	5.75	5.97	2	4	2203	150	2	20	54	20	514,660	1,827,794	20,586	38,853	1,605	12,068	73,112	52,525	0.721	155,014
4.82	5.75	4.28	1	4	530	150	0	20	90	20	591,580	1,747,412	23,663	37,032	1,773	7,429	69,896	46,233	0.689	155,014
4.82	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	0	0	20	0	0	18,000	5,093,536	720	8,813	4,380	189,829	203,741	203,021	2.008	0
3 Additional FBCFs for (s3, w2)																				
0.92	5.25	5.97	2	3	2794	200	4	0	162	20	870,878	1,677,960	34,835	29,443	2,840	0	67,118	32,283	0.661	186,374
1.98	5.25	5.97	2	3	256	200	4	0	162	20	870,878	1,677,960	34,835	29,443	2,840	0	67,118	32,283	0.661	186,374
4.82	5.25	5.97	2	3	2727	150	1	20	54	20	511,234	1,911,481	20,449	38,995	1,604	15,411	76,459	56,010	0.754	139,780
7.92	5.25	5.97	2	3	3641	150	0	20	54	20	507,808	2,174,201	20,312	39,347	1,556	25,753	86,968	66,656	0.857	139,780
Sorting on Life Cycle Cost Only as FBCF Increases for (s3, w2)																				
0.92	5.25	5.97	2	3	1	100	0	20	0	20	266,100	1,064,739	10,644	6,173	3,480	22,293	42,590	31,946	0.42	93,187
1.98	5.25	5.97	2	3	4	150	40	0	144	20	836,278	1,552,548	33,451	24,261	4,390	0	62,102	28,651	0.612	139,780
4.82	5.25	5.97	2	3	4	150	40	0	144	20	836,278	1,552,548	33,451	24,261	4,390	0	62,102	28,651	0.612	139,780
7.92	5.25	5.97	2	3	4	150	40	0	144	20	836,278	1,552,548	33,451	24,261	4,390	0	62,102	28,651	0.612	139,780

Table 27. Energy system specifications a for 25-year life cycle.

Tables 27 through 29 provide detailed specifications for all 28 energy system designs contained in the optimal energy rubric in addition to the FBCF sensitivity analysis. Rows that are similar color indicate identical energy systems designs. The generator only solution is provided at the bottom of the first set of data (row 29). The second set of four rows provides data for the FBCF run. The last set provides an opportunity to compare energy system designs from the FBCF analysis, as if life cycle cost was the only need. This is accomplished by sorting the database analysis exclusively on life cycle cost.

Fully Burdened Cost of Fuel ($/Liter)	Solar Irradiance (kWh/m2/day)	Wind Speed (m/sec)	Wind Matrix Coordinate (w)	Solar Matrix Coordinate (s)	System ID (#)	PV (kW)	Wind Turbines (#)	Wind Production (kWh/yr)	Gen Production (kWh/yr)	Tot. Electrical Production (kWh/yr)	AC Primary Load Served (kWh/yr)	Ren. Fraction (#)	Cap. Shortage (kWh/yr)	Cap. Shortage Frac. (#)	Unmet Load (kWh/yr)	Unmet Load Frac. (#)	Excess Electricity (kWh/yr)
4.82	4.25	8.59	7	1	615	150	18	42,062	6,254	156,712	101,470	0.96	0	0	0	0	37,491
4.82	4.25	7.85	6	1	861	150	18	35,762	8,164	152,322	101,470	0.95	0	0	0	0	32,700
4.82	4.25	7.55	5	1	1188	150	16	29,428	9,135	146,960	101,470	0.94	0	0	0	0	26,923
4.82	4.25	7.48	4	1	1011	200	14	25,265	5,605	175,398	101,470	0.97	0	0	0	0	55,191
4.82	4.25	6.73	3	1	2185	200	5	7,172	8,488	160,188	101,470	0.95	0	0	0	0	38,550
4.82	4.25	5.97	2	1	2172	200	2	2,139	9,589	156,257	101,470	0.94	0	0	0	0	34,206
4.82	4.25	4.28	1	1	1270	200	1	399	9,959	154,886	101,470	0.94	0	0	0	0	32,711
4.82	4.75	8.59	7	2	605	150	16	37,388	4,841	166,430	101,470	0.97	0	0	0	0	46,944
4.82	4.75	7.85	6	2	1155	150	12	23,841	6,895	154,937	101,470	0.96	0	0	0	0	34,556
4.82	4.75	7.55	5	2	972	150	14	25,750	6,694	156,645	101,470	0.96	0	0	0	0	36,372
4.82	4.75	7.48	4	2	975	150	14	25,265	6,781	156,247	101,470	0.96	0	0	0	0	35,939
4.82	4.75	6.73	3	2	1878	150	10	14,343	9,042	147,586	101,470	0.94	0	0	0	0	26,437
4.82	4.75	5.97	2	2	2465	200	0	0	7,633	173,235	101,470	0.96	0	0	0	0	50,956
4.82	4.75	4.28	1	2	1342	200	0	0	7,633	173,235	101,470	0.96	0	0	0	0	50,956
4.82	5.25	8.59	7	3	642	150	16	37,388	3,885	181,053	101,470	0.98	0	0	0	0	61,576
4.82	5.25	7.85	6	3	1174	150	12	23,841	5,633	169,254	101,470	0.97	0	0	0	0	48,845
4.82	5.25	7.55	5	3	1803	150	8	14,714	6,618	161,112	101,470	0.96	0	0	0	0	39,937
4.82	5.25	7.48	4	3	1398	150	10	18,047	6,237	164,064	101,470	0.96	0	0	0	0	43,200
4.82	5.25	6.73	3	3	1743	150	8	11,475	7,216	158,470	101,470	0.95	0	0	0	0	37,029
4.82	5.25	5.97	2	3	2727	150	1	1,070	9,481	150,330	101,470	0.94	0	0	0	0	28,051
4.82	5.25	4.28	1	3	1571	150	1	399	9,620	149,798	101,470	0.94	0	0	0	0	27,451
4.82	5.75	8.59	7	4	747	100	16	37,388	6,304	147,035	101,470	0.96	0	0	0	0	27,465
4.82	5.75	7.85	6	4	635	100	20	39,736	6,340	149,419	101,470	0.96	0	0	0	0	29,806
4.82	5.75	7.55	5	4	1742	150	8	14,714	5,534	175,262	101,470	0.97	0	0	0	0	54,086
4.82	5.75	7.48	4	4	1430	150	10	18,047	5,170	178,231	101,470	0.97	0	0	0	0	57,345
4.82	5.75	6.73	3	4	1874	150	6	8,606	6,201	169,820	101,470	0.96	0	0	0	0	48,108
4.82	5.75	5.97	2	4	2203	150	2	2,139	7,391	164,544	101,470	0.96	0	0	0	0	42,274
4.82	5.75	4.28	1	4	530	150	0	0	4,597	159,611	101,470	0.97	0	0	0	0	37,212
4.82	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	0	0	0	101,470	101,470	101,470	0	0	0	0	0	0
3 Additional FBCFs for (s3, w2)																	
0.92	5.25	5.97	2	3	2794	200	4	4,278	0	190,652	101,470	1	0	0	0	0	68,557
1.98	5.25	5.97	2	3	256	200	4	4,278	0	190,652	101,470	1	0	0	0	0	68,557
4.82	5.25	5.97	2	3	2727	150	1	1,070	9,481	150,330	101,470	0.94	0	0	0	0	28,051
7.92	5.25	5.97	2	3	3641	150	0	0	9,608	149,388	101,470	0.94	0	0	0	0	27,013
Sorting on Life Cycle Cost Only as FBCF Increases for (s3, w2)																	
0.92	5.25	5.97	2	3	1	100	0	0	58,782	151,968	101,470	0.61	0	0	0	0	45,755
1.98	5.25	5.97	2	3	4	150	40	42,784	0	182,563	101,470	1	0	0	0	0	62,744
4.82	5.25	5.97	2	3	4	150	40	42,784	0	182,563	101,470	1	0	0	0	0	62,744
7.92	5.25	5.97	2	3	4	150	40	42,784	0	182,563	101,470	1	0	0	0	0	62,744

Table 28. Energy system specifications for a 25-year life cycle (continued).

Fully Burdened Cost of Fuel ($/Liter)	Solar Irradiance (kWh/m2/day)	Wind Speed (m/sec)	Wind Matrix Coordinate (w)	Solar Matrix Coordinate (s)	System ID (#)	PV (kW)	Wind Turbines (#)	Diesel (L/yr)	CO2 Emissions (kg/yr)	CO Emissions (kg/yr)	UHC Emissions (kg/yr)	PM Emissions (kg/yr)	SO2 Emissions (kg/yr)	NOx Emissions (kg/yr)	Gen Fuel (L/yr)	Gen Hours (hr/yr)	Gen Starts (starts/yr)	Gen Life (yr)	Battery Autonomy (hr)	Battery Throughput (kWh/yr)	Battery Life (yr)	Lifetime Batteries Required (#)	SAW Score
4.82	4.25	8.59	7	1	615	150	18	2,103	5,537	14	2	1	11	122	2,103	337	22	44.51	24.61	40,958	4.2	321.429	0.807
4.82	4.25	7.85	6	1	861	150	18	2,747	7,233	18	2	1	15	159	2,747	441	31	34.01	24.61	43,561	4	337.500	0.794
4.82	4.25	7.55	5	1	1188	150	16	3,073	8,091	20	2	2	16	178	3,073	493	35	30.43	24.61	46,019	3.8	355.263	0.790
4.82	4.25	7.48	4	1	1011	200	14	1,902	5,008	12	1	1	10	110	1,902	313	22	47.92	24.61	47,139	3.7	364.865	0.789
4.82	4.25	6.73	3	1	2185	200	5	2,863	7,539	19	2	1	15	166	2,863	463	30	32.4	24.61	55,948	3.1	435.484	0.782
4.82	4.25	5.97	2	1	2172	200	2	3,228	8,500	21	2	2	17	187	3,228	519	34	28.9	24.61	58,526	3	450.000	0.782
4.82	4.25	4.28	1	1	1270	200	1	3,359	8,845	22	2	2	18	195	3,359	543	35	27.62	24.61	59,280	2.9	465.517	0.782
4.82	4.75	8.59	7	2	605	150	16	1,637	4,312	11	1	1	9	95	1,637	267	18	56.18	24.61	42,415	4.1	329.268	0.814
4.82	4.75	7.85	6	2	1155	150	12	2,320	6,110	15	2	1	12	135	2,320	373	25	40.21	24.61	48,155	3.6	375.000	0.804
4.82	4.75	7.55	5	2	972	150	14	2,253	5,932	15	2	1	12	131	2,253	362	24	41.44	24.61	47,516	3.6	375.000	0.800
4.82	4.75	7.48	4	2	975	150	14	2,279	6,002	15	2	1	12	132	2,279	365	24	41.1	24.61	47,713	3.6	375.000	0.800
4.82	4.75	6.73	3	2	1878	150	10	3,054	8,042	20	2	1	16	177	3,054	496	33	30.24	24.61	52,910	3.3	409.091	0.790
4.82	4.75	5.97	2	2	2465	200	0	2,585	6,807	17	2	1	14	150	2,585	423	28	35.46	24.61	59,885	2.9	465.517	0.791
4.82	4.75	4.28	1	2	1342	200	0	2,585	6,807	17	2	1	14	150	2,585	423	28	35.46	24.61	59,885	2.9	465.517	0.792
4.82	5.25	8.59	7	3	642	150	16	1,315	3,464	9	1	1	7	76	1,315	215	15	69.77	24.61	42,362	4.1	329.268	0.817
4.82	5.25	7.85	6	3	1174	150	12	1,912	5,036	12	1	1	10	111	1,912	315	23	47.62	24.61	48,297	3.6	375.000	0.809
4.82	5.25	7.55	5	3	1803	150	8	2,235	5,886	15	2	1	12	130	2,235	363	24	41.32	24.61	52,983	3.3	409.091	0.806
4.82	5.25	7.48	4	3	1398	150	10	2,110	5,556	14	2	1	11	122	2,110	344	23	43.6	24.61	51,188	3.4	397.059	0.805
4.82	5.25	6.73	3	3	1743	150	8	2,436	6,415	16	2	1	13	141	2,436	395	26	37.97	24.61	54,684	3.2	421.875	0.799
4.82	5.25	5.97	2	3	2727	150	1	3,197	8,420	21	2	2	17	185	3,197	517	33	29.01	24.61	59,958	2.9	465.517	0.798
4.82	5.25	4.28	1	3	1571	150	1	3,242	8,537	21	2	2	17	188	3,242	523	33	28.68	24.61	60,293	2.9	465.517	0.799
4.82	5.75	8.59	7	4	747	100	16	2,123	5,591	14	2	1	11	123	2,123	342	23	43.86	24.61	43,103	4	337.500	0.824
4.82	5.75	7.85	6	4	635	100	20	2,136	5,624	14	2	1	11	124	2,136	344	23	43.6	24.61	43,430	4	337.500	0.814
4.82	5.75	7.55	5	4	1742	150	8	1,886	4,966	12	1	1	10	109	1,886	314	23	47.77	24.61	53,096	3.3	409.091	0.810
4.82	5.75	7.48	4	4	1430	150	10	1,766	4,651	11	1	1	9	102	1,766	296	22	50.68	24.61	51,314	3.4	397.059	0.809
4.82	5.75	6.73	3	4	1874	150	6	2,101	5,531	14	2	1	11	122	2,101	344	23	43.6	24.61	56,328	3.1	435.484	0.806
4.82	5.75	5.97	2	4	2203	150	2	2,504	6,593	16	2	1	13	145	2,504	410	28	36.59	24.61	59,795	2.9	465.517	0.806
4.82	5.75	4.28	1	4	530	150	0	1,541	4,058	10	1	1	8	89	1,541	245	11	61.22	41.02	62,394	4.6	489.130	0.807
4.82	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	Generator ONLY	0	0	39,384	103,710	256	28	19	208	2,284	39,384	8,760	1	1.71	0	0			
3 Additional FBCFs for (s3, w2)																							
0.92	5.25	5.97	2	3	2794	200	4	0	0	0	0	0	0	0	0	0	0	1000	73.84	60,146	8.6	470.930	0.780
1.98	5.25	5.97	2	3	256	200	4	0	0	0	0	0	0	0	0	0	0	1000	73.84	60,146	8.6	470.930	0.795
4.82	5.25	5.97	2	3	2727	150	1	3,197	8,420	21	2	2	17	185	3,197	517	33	29.01	24.61	59,958	2.9	465.517	0.799
7.92	5.25	5.97	2	3	3641	150	0	3,252	8,563	21	2	2	17	189	3,252	531	33	28.25	24.61	60,547	2.9	465.517	0.800
Sorting on Life Cycle Cost Only as FBCF Increases for (s3, w2)																							
0.92	5.25	5.97	2	3	1	100	0	24,231	63,809	158	17	12	128	1,405	24,231	5,960	376	2.52	0	0	10	0.000	0.706
1.98	5.25	5.97	2	3	4	150	40	0	0	0	0	0	0	0	0	0	0	1,000.00	65.64	46,204	10	360.000	0.762
4.82	5.25	5.97	2	3	4	150	40	0	0	0	0	0	0	0	0	0	0	1000	65.64	46,204	10	360.000	0.733
7.92	5.25	5.97	2	3	4	150	40	0	0	0	0	0	0	0	0	0	0	1000	65.64	46,204	10	360.000	0.734

Table 29. Energy system specifications for a 25-year life cycle (continued).

Appendix B—Input Data

	w1	w2	w3	w4	w5	w6	w7	w8
W/m2 at 50m	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800

	W/m2 at 50m	Annual Average Wind Speed m/sec				Weibull K	Autocorrelation Factor	Diurnal Pattern Strength	Hour of Peak Windspeed
w1	0-100	4.45	Lattitude	30.30	Model Input File	1.72	0.9	0.15	17
			Longitude	65.51					
w1	0-100	5.26	Lattitude	33.05	Model Input File	2.24	0.9	0.15	17
			Longitude	68.15					
w1	0-100	4.36	Lattitude	33.94	Model Input File	1.46	0.9	0.15	17
			Longitude	66.04					
w1	0-100	4.97	Lattitude	35.94	Model Input File	2.02	0.9	0.15	17
			Longitude	67.52					
w1	0-100	4.00	Lattitude	35.43	Model Input File	1.58	0.9	0.15	17
			Longitude	71.44					
w1	0-100	3.41	Lattitude	37.00	Model Input File	1.32	0.9	0.15	17
			Longitude	70.87					
	Variance	0.44			Variance	0.12			
	Average	**4.41**			**Average**	**1.72**			
w2	100-200	4.13	Lattitude	37.00	Model Input File	1.48	0.9	0.15	17
			Longitude	65.02					
w2	100-200	3.67	Lattitude	34.55	Model Input File	1.1	0.9	0.15	17
			Longitude	64.99					
w2	100-200	4.44	Lattitude	30.15	Model Input File	1.72	0.9	0.15	17
			Longitude	64.25					
w2	100-200	4.16	Lattitude	30.03	Model Input File	1.44	0.9	0.15	17
			Longitude	61.46					
w2	100-200	4.54	Lattitude	35.11	Model Input File	2.08	0.9	0.15	17
			Longitude	62.85					
w2	100-200	3.96	Lattitude	36.91	Model Input File	1.5	0.9	0.15	17
			Longitude	66.90					
	Variance	0.10			Variance	0.11			
	Average	**4.15**			**Average**	**1.55**			
0-200 Average (w1 & w2)		**4.28**							
w3	200-300	5.84	Lattitude	36.81	Model Input File	1.68	0.9	0.15	17
			Longitude	69.10					
w3	200-300	6.6	Lattitude	34.33	Model Input File	1.8	0.9	0.15	17
			Longitude	68.01					
w3	200-300	5.47	Lattitude	31.23	Model Input File	1.54	0.9	0.15	3
			Longitude	62.57					
	Variance	0.33			Variance	0.02			
	Average	**5.97**			**Average**	**1.67**			

w4	300-400	6.17	Lattitude	37.51	Model Input File	1.54	0.9	0.15	17
			Longitude	69.87					
w4	300-400	6.56	Lattitude	30.85	Model Input File	1.86	0.9	0.15	3
			Longitude	62.87					
w4	300-400	7.47	Lattitude	32.39	Model Input File	2.12	0.9	0.15	17
			Longitude	67.26					
	Variance	0.45			Variance	0.08			
	Average	**6.73**			**Average**	**1.84**			
w5	400-500	7.35	Lattitude	34.02	Model Input File	1.96	0.9	0.15	3
			Longitude	61.60					
w5	400-500	7.35	Lattitude	32.68	Model Input File	1.96	0.9	0.15	3
			Longitude	60.84					
w5	400-500	7.74	Lattitude	34.78	Model Input File	1.9	0.9	0.15	17
			Longitude	70.33					
	Variance	0.05			Variance	0.00			
	Average	**7.48**			**Average**	**1.94**			
w6	500-600	7.95	Lattitude	34.75	Model Input File	1.78	0.9	0.15	17
			Longitude	70.33					
w6	500-600	7.7	Lattitude	33.07	Model Input File	1.8	0.9	0.15	3
			Longitude	60.81					
w6	500-600	7.01	Lattitude	32.14	Model Input File	1.62	0.9	0.15	3
			Longitude	61.74					
	Variance	0.24			Variance	0.01			
	Average	**7.55**			**Average**	**1.73**			

w7	600-800	7.51	Lattitude	31.79	Model Input File	1.66	0.9	0.15	3
			Longitude	61.18					
w7	600-800	7.4	Lattitude	31.61	Model Input File	1.46	0.9	0.15	3
			Longitude	61.60					
w7	600-800	8.65	Lattitude	36.21	Model Input File	1.8	0.9	0.15	17
			Longitude	70.98					
	Variance	0.48			Variance	0.03			
	Average	**7.85**			**Average**	**1.64**			
w8	> 800	9.28	Lattitude	32.49	Model Input File	1.86	0.9	0.15	3
			Longitude	61.32					
w8	> 800	8.24	Lattitude	32.01	Model Input File	1.46	0.9	0.15	3
			Longitude	61.12					
w8	> 800	8.24	Lattitude	31.76	Model Input File	1.46	0.9	0.15	3
			Longitude	61.40					
	Variance	0.36			Variance	0.05			
	Average	**8.59**			**Average**	**1.59**			
					Overall Average	**1.71**	0.9	0.15	17
					Average Deviatioı	0.21			

Figure 32. Random sampling within each wind class.

Figure 32 contains data samples from random locations in Afghanistan within each wind category. The category averages represent the wind classes in the rubric.

Figures 33 through 40 are HOMER screenshots and provide details about the input data used in the simulation.

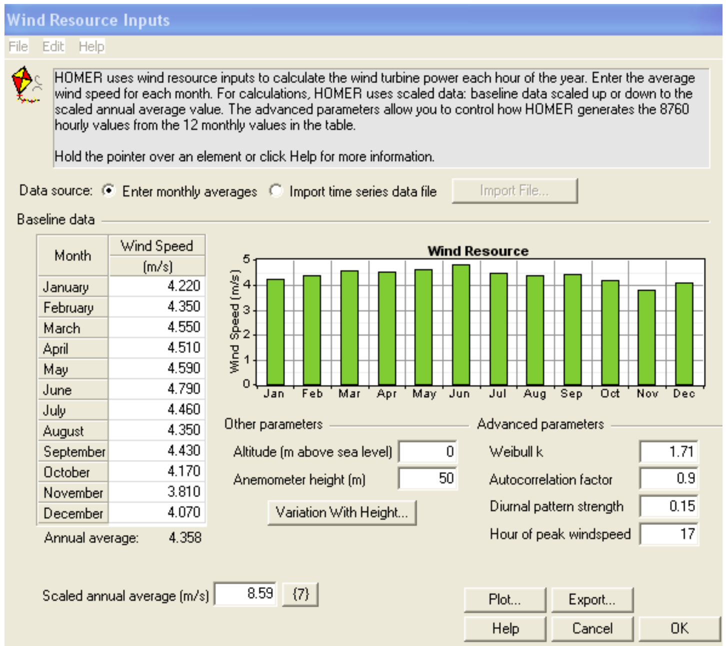

Figure 33. Wind speed input data. (From: NREL, 2011)

Figure 33 contains actual wind data from a location in Afghanistan. For the simulation, this data is scaled to the annual averages for each wind class as determined from Figure 32.

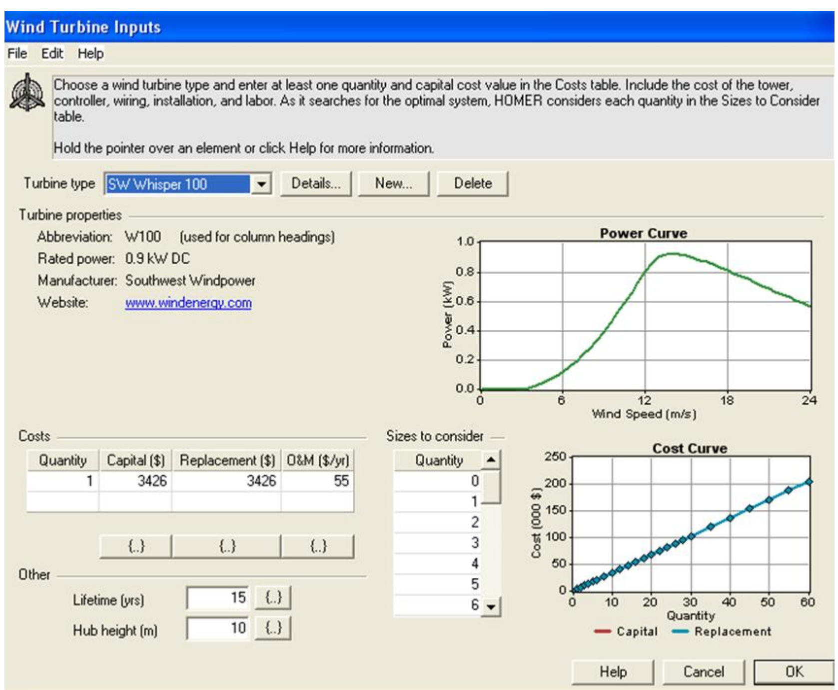

Figure 34. Wind turbine input data. (From: NREL, 2011)

Figure 34 shows cost data and the hub height. The hub height is set to 10 meters, for rooftop application, as shown in the bottom left corner of Figure 34.

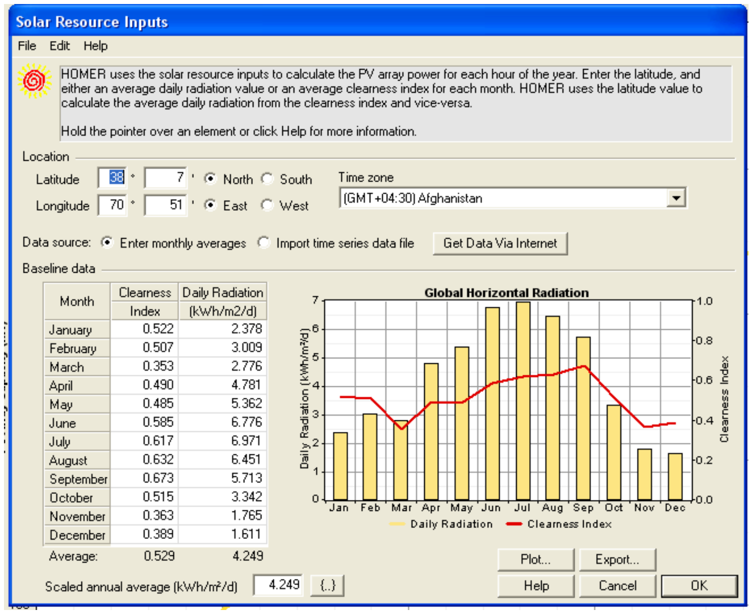

Figure 35. Solar irradiance input data. (From: NREL, 2011)

Figure 35 shows monthly solar irradiance input data that is scaled using the averages from Table 8.

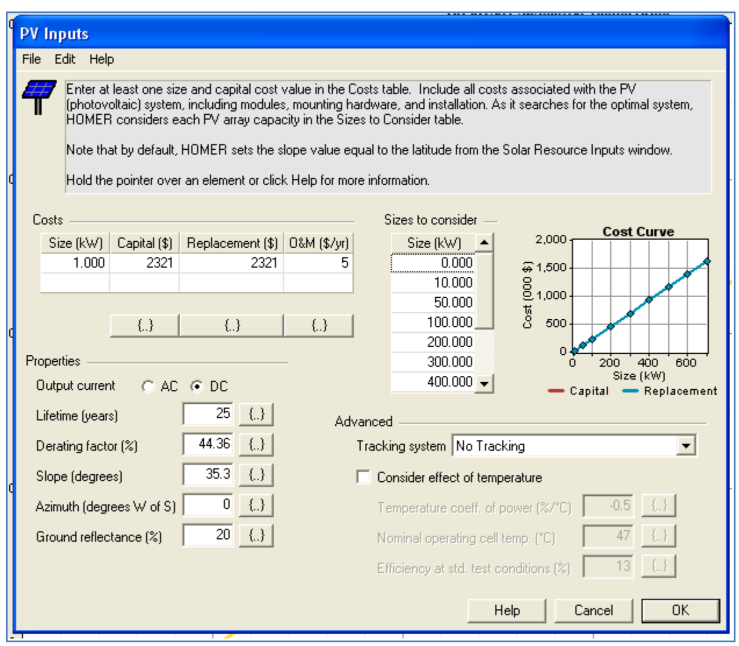

Figure 36. Solar panel input specifications. (From: NREL, 2011)

Figure 36 shows solar panel cost data and other characteristics to include the derating factor, set to 44.36.

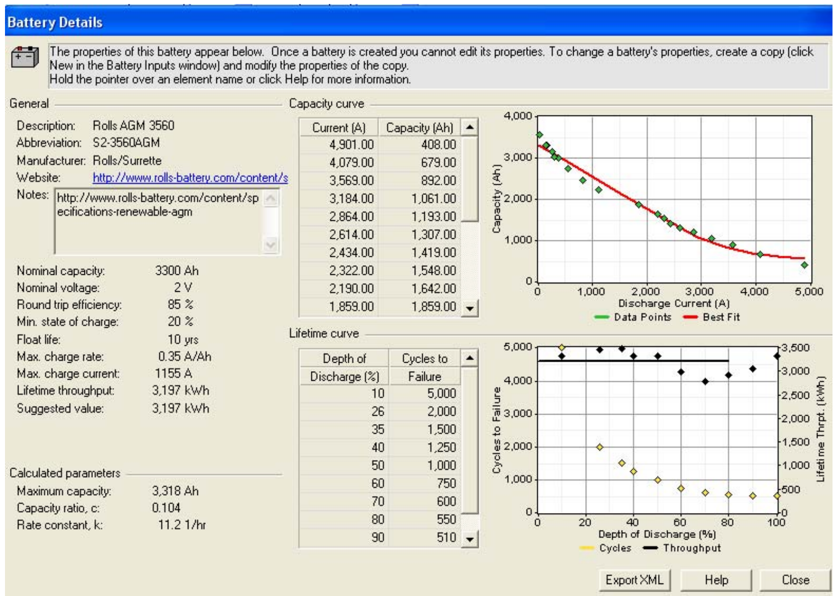

Figure 37. Battery input specifications. (From: NREL, 2011)

Figure 37 shows the battery capacity and lifetime characteristics that are calculated using data available from Rolls website.

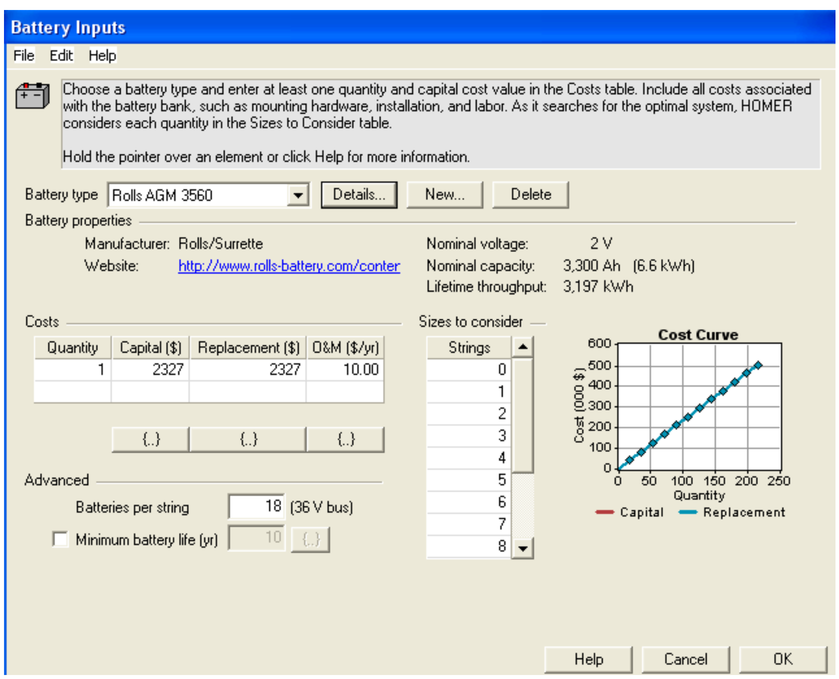

Figure 38. Battery cost data. (From: NREL, 2011)

Figure 38 shows battery cost and string size, set to 18 batteries per string.

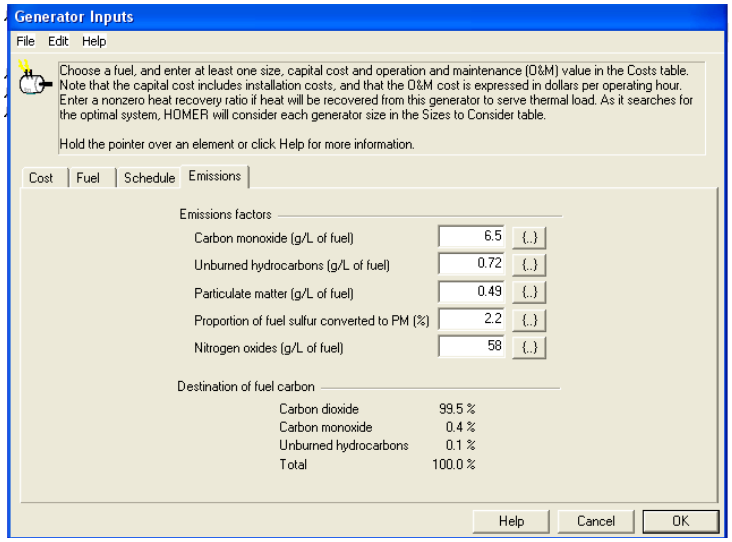

Figure 39. Generator input data. (From: NREL, 2011)

HOMER's default values for emission factors are set as indicated in Figure 39.

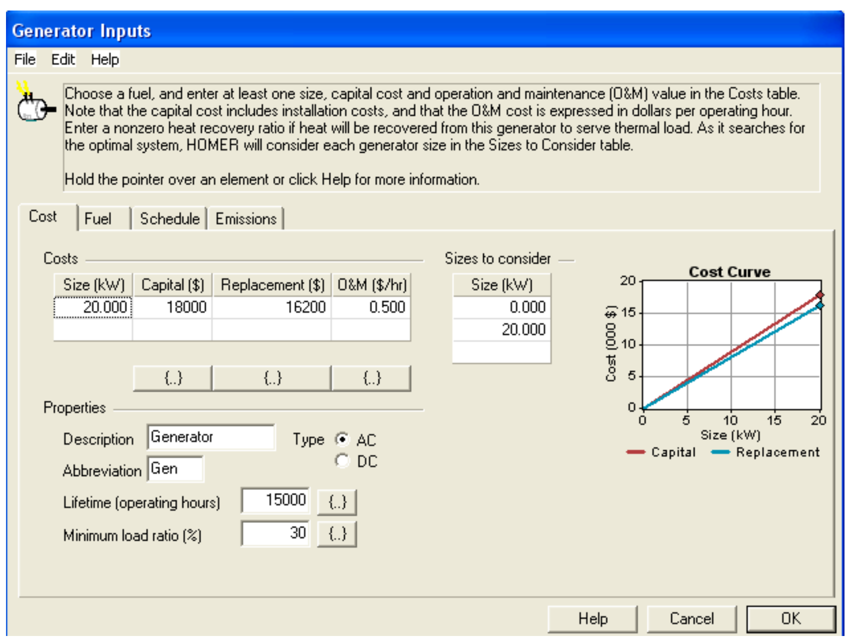

Figure 40. Generator cost data. (From: NREL, 2011)

Generator cost data and lifetime operating hours are shown in Figure 40. Figures 41 through 44 illustrate the economic input considerations that HOMER considers when simulating the results.

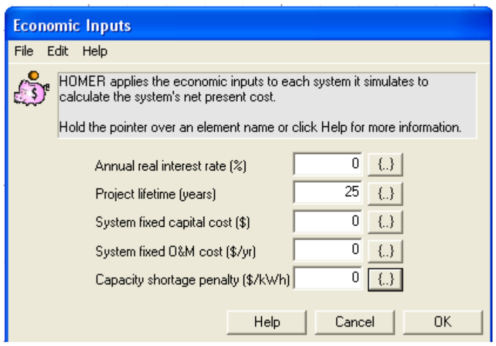

Figure 41. Economic input variables. (From: NREL, 2011)

Figure 41 shows that the project lifetime is set to 25 years. The annual real interest rate, *i* is calculated using the equation in the HOMER help file, shown in Figure 42.

$$i = \frac{i' - f}{1 + f}$$

i = real interest rate
i' = nominal interest rate (the rate at which you could get a loan)
f = annual inflation rate

Figure 42. Real interest rate formula. (From: NREL, 2011)

The variables in Figure 42 are defined in Figure 43. The variables were determined by looking up current interest rate and inflation rate values from the websites in Figure 44.

i' = 3.25%
f = 6%

Figure 43. Interest rate and inflation values. (From: NREL, 2011)

http://www.bankrate.com/rates/interest-rates/wall-street-prime-rate.aspx	
http://inflationdata.com/inflation/Inflation/AnnualInflation.asp	

Figure 44. Websites used to determine interest rate and inflation values.

When using these values, the resulting real interest rate is -0.03. When this value is used as input for the interest rate box, HOMER automatically rounds this value to zero as shown in the top input field in Figure 41.

Although HOMER permits the user to input fiscal emission penalties, as shown in Figure 45, no emission penalties are imposed into the simulation, since environmental impact is already a need and key system attribute.

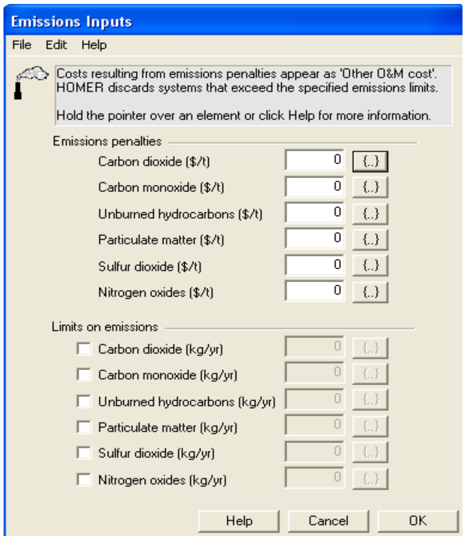

Figure 45. Emission penalty input data. (From: NREL, 2011)

Since the purpose is to choose a system that fits the ExFOB defined energy profile, capacity shortage is not permitted, as shown in Figure 46. Furthermore, there is not a need for operating reserve; the system simply has to be capable of meeting the load profile with 6% hourly and daily variation (already accounted for in the profile).

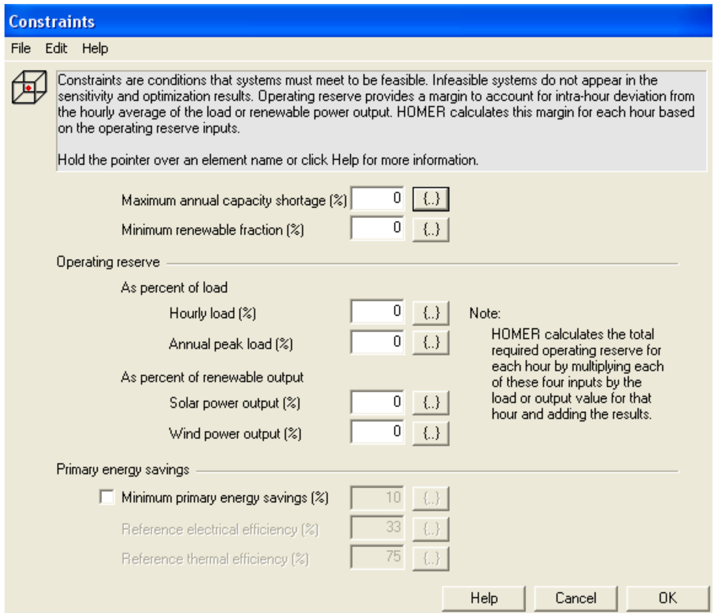

Figure 46. Energy production/shortage constraints. (From: NREL, 2011)

Shown in Figure 47, simulation step time remains at the default value of 60 minutes per time step. One-hour time steps is commensurate with the hourly load profile data supplied. The set point state of charge parameter controls the state at which the system will stop charging the battery bank. This value, in Figure 47, remains set at the default value of 80%. The point at which the battery bank no longer provides power is set in the battery detail menu and is set at 20% state of charge, shown in Figure 37 as minimum state of charge.

In this simulation, systems with multiple generators are not allowed, as shown in Figure 47, and systems are not allowed to have a generator capacity less than that of the peak load. With this approach, maximum security is achieved by permitting the entire load to be satisfied exclusively by the generator in the event of a system failure.

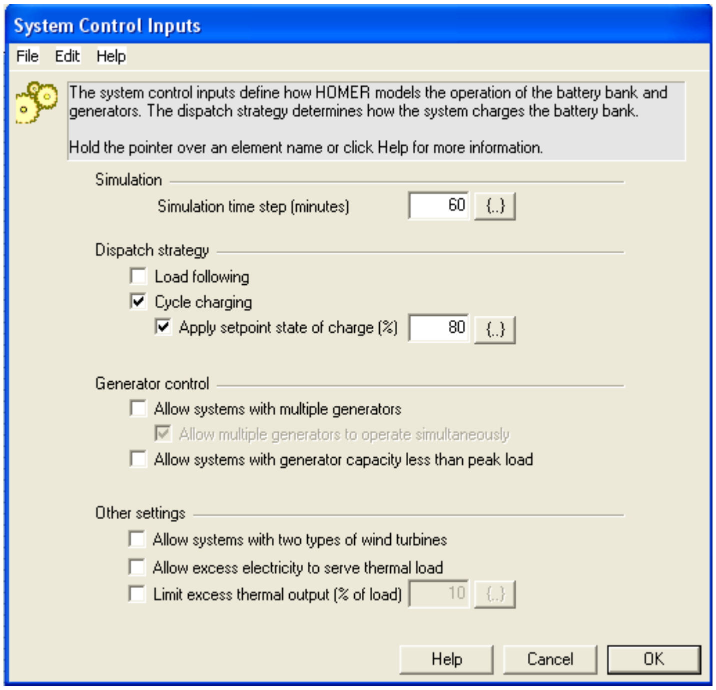

Figure 47. Simulation control settings. (From: NREL, 2011)

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